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IEA SOLAR HEATING AND COOLING PROGRAM

TASK 18

ADVANCED GLAZING
and
ASSOCIATED MATERIALS FOR SOLAR AND BUILDING APPLICATIONS

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Final Report
Subtask A2/A3: Modeling and Control Strategies

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A. SUMMARY

Researchers participating in IEA/SHC Task 18 on advanced glazing materials have as their primary objective the development of new innovative glazing products such as high performance glazings, wavelength selective glazings, chromogenic optical switching devices, and light transport mechanisms that will lead to significant energy use reductions and increased comfort in commercial and residential buildings. Part of the Task 18 effort involves evaluation of the energy and comfort performance of these new glazings through the use of various performance analysis simulation tools. Ten countries (Australia, Denmark, Finland, Germany, Italy, Norway, Spain, Switzerland, and the United States) have contributed to this multi-year simulation study to better understand the complex heat transfer interactions that determine window performance. Each country has selected particular simulation programs, geographic locations, building types, window systems, and control strategies for their individual analysis. This report summarizes the results obtained by the research organizations.

B. INTRODUCTION

A major focus in Subtask A, categorized as the Modeling and Control Strategies Project, involves evaluating the energy and comfort performance of advanced glazing systems and dynamic control strategies in realistic commercial and residential building environments through mathematical simulation of the heat transfer processes. Another interest is to evaluate the ability of current window and building simulation tools to properly characterize the dynamic and annual performance of these systems and improve tools as necessary to create common technical approaches for simulation. Eventually, it is hoped to create models that can meet the simulation needs of groups such as ISO, CEN, and NFRC in developing national and international window rating systems.

The USA is coordinating the efforts of researchers from ten countries participating in the Modeling and Control Strategies Project. Countries include: Australia, Denmark, Finland, Germany, Italy, Norway, Spain, Sweden, Switzerland, and the United States. The remainder of this report discusses in more detail the definition phase of the project and specific simulation results of participating countries.

C. PROJECT DEFINITION

The Modeling and Control Strategies Project was structured so that participating countries could evaluate the performance of advanced glazings within the context of their own particular environment. This includes not only geographic location, but also the commercial and/or residential buildings simulated as well as window systems and control strategies analyzed. In addition, each country had the option of using whatever analysis tool best fit their needs and desires. Selected simulation programs included: CHEETAH (AUS); DOE-2.1E (AUS, USA); HELIOS (CH); TRNSYS (FIN, IT, GER, NOR); TRANE (SP); and TSBI3 (DK). We see the results from each country as complementary, yet totally independent and individualized.

Table 1 shows the cities for each country whose weather patterns were simulated. Locations vary from Darwin, Australia at 12 degrees south latitude characterized as tropical, hot and humid to Sodankylä , Finland at 67 degrees north latitude which has very cold winters and mild summers. While most of the locations can be associated with significant winter heating requirements primarily because they are located in northern Europe, cities located in Australia, Italy, and the United States insured adequate cooling performance analysis for the selected advanced glazings.

Both commercial and residential buildings have been simulated by most countries. The commercial buildings varied from prototypical single-floor office building modules to multi-floor buildings with ground floors, intermediate floors, and rooftop floors. Residential buildings were either single-story and two-story with floor plans and construction typical of the participating country. The orientation of each of these buildings was varied so that its effect on window performance was also obtained.

Tables 2 and 3 show the advanced glazings and control strategies that were analyzed by each country. We see that the representative glazings reflect an interest in one or more of the glazing property characteristics that effect energy and comfort performance; i.e. thermal, solar, and optical. For example, aerogel, superinsulated, and evacuated glazings focus on insulation performance as well as solar gain performance; whereas, angular selective, electrochromic, and solar control systems tend to focus on the solar and optical characteristic performance. In all cases, however, performance of these advanced glazings were referenced to baseline glazings.

Control strategies effecting both the building envelope and lighting system were studied. Envelope strategies included those being used with electrochromic windows to control state-switching and those used with conventional shading systems such as venetian blinds, diffusing shades, etc. Lighting system strategies were related specifically to window daylight performance and several types of dimming controls were analyzed.

TABLE 1
Geographic Locations

Location	Latitude	Weather	Heating Degree Days Base Temp 18C (65F)	
Australia				
Canberra	35degS	Cool/temperate/dry	HDD=2160	(3888)
Darwin	12degS	Tropical/hot/humid	HDD=0	(0)
Sydney	34degS	Mild winter, warm humid summer	HDD=743	(1337)
Denmark				
Copenhagen	56degN	Temperate	HDD=2990	(5382)
Finland				
Helsinki	60degN	Cold winter, mild summer	HDD=4716	(8489)
Jyväskylä	62degN	Cold winter, mild summer	HDD=5274	(9493)
Sodankylä	67degN	Cold winter, mild summer	HDD=7112	(12802)
Germany				
Bremerhaven	54degN	Cool maritime	HDD=4090	(7362)
Freiburg	48degN	Mild continental	HDD=3400	(6120)
Italy				
Milano	45degN	Cold winter, hot/humid summer	HDD=2615	(4707)
Roma	42degN	Mild winter, hot/humid summer	HDD=1606	(2891)
Norway				
Oslo	60degN	Cold winter, mild summer	HDD=4077	(7339)
Tromsø	70degN	Cold winter, mild summer	HDD=6029	(10852)
Spain				
Madrid	40degN	Mild winter, hot,dry summer	HDD=1800	(3240)
Seville	37degN	Mild winter, hot,dry summer	HDD=962	(1732)
Cadiz	36degN	Mild winter, hot,humid summer	HDD=660	(1188)
Switzerland				
Davos	47degN	Alpine	HDD= 5866	(10558)
Geneva	46degN	Cold winter, mild summer	HDD= 3191	(5743)
Magadino	46degN	Moderate winter, warm summer	HDD= 2919	(5254)
Zurich	47degN	Cold winter, mild summer	HDD= 3469	(6244)
United States				
Blythe	33degN	Mild winter, hot/dry summer	HDD=580	(1044)

Madison	43degN	Cold winter, hot/humid summer	HDD=4347	(7825)
Miami	26degN	Warm winter, hot/humid summer	HDD=103	(185)
Phoenix	33degN	Mild winter, hot/dry summer	HDD=1066	(1919)

TABLE 2

Advanced Glazings Studied

Commercial Buildings

Aerogel	(DK, NOR)
Angular selective	(USA)
Electrochromic	(FIN, NOR, IT, USA)
Solar Control	(SP)
Superinsulated	(FIN, CH)

Residential Buildings

Aerogel	(DK, NOR)
Electrochromic	(USA)
Evacuated	(AUS, NOR, USA)
Superinsulated	(CH, FIN, NOR, USA)
Thermotropic	(FRG)
TIM	(CH)

TABLE 3

Control Strategies Studied

Commercial Buildings

Electrochromic devices	
Daylight illuminance	(FIN, IT, USA)
Solar radiation	(NOR, IT, USA)
Space thermal load	(USA)
Space temperature	(NOR, IT)
Shading devices	
Solar radiation	(CH)

Residential Buildings

Electrochromic devices	
Solar radiation	(USA)
Space thermal load	(USA)
Outside Air Temperature	(USA)
Thermotropic devices	
Surface temperature	(FRG)

Shading devices
Solar radiation (USA)

D. SIMULATION RESULTS

AUSTRALIA

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SIMULATION RESULTS: Australia

The simulation studies presented for Australia are for residential applications. Conventional single- and double-pane glazings have been compared to high performance solar control glazings and highly insulated glazings in three climate zones. The performances of the window systems in this study span the range of climates where most of the Australian population lives. The three climates selected for the simulations range from the tropical heat of Darwin, through Sydney with its Mediterranean climate and mild winter, to cool temperate Canberra with sunny, frosty winters and hot dry summers. The thermal modeling software used was CHEETAH, which is a PC-based dynamic program based on the ASHRAE response-factor method. It is the chosen tool for the development of Australia's Nationwide House Energy Rating Scheme (NatHERS) and the new Window Energy Rating Scheme (WERS).

Discussion

The Australian house used for the window energy modeling is a rectangular single-story, slab-on-grade design of 170 m^2 (1830 ft^2) floor area with construction typical for houses built after about 1970 in the eastern states of Australia. It has been chosen to represent neither the best nor the worst in terms of energy efficiency. The house's living areas face the equator and the glazing areas are distributed thus: north (equator-facing) 21.1 m^2 (227 ft^2); east 2.1 m^2 (22.6 ft^2); south 14.8 m^2 (159 ft^2); and west 2.0 m^2(21.5 ft^2). No internal shading devices were assumed in the simulations. No curtains were allowed for in terms of additional night-time insulation. However eaves 600mm (2 ft) deep and 250mm (10 in) above the window head were assumed for the north and south facades of the bulding.

The house has a 100mm (4-inch) slab on ground and has a softwood frame with an external brick-veneer skin and an internal plasterboard (drywall) lining. Ceiling and external wall added insulation levels are, respectively, 3.5 m^2.K/W (19.9 h.ft^2.°F/Btu) and 1.5 m^2.K/W (8.5 h.ft^2.°F/Btu). In addition, reflective foil laminate is fitted under the roofing tiles. Apart from the floor slab which is partly carpeted, there is little thermal mass apart from incidental amounts provided by objects in the house. Internal heat gains corresponding to lights and applances for a typical family of four were allowed for.

Whole-house space conditioning was defined at setpoint temperatures of 20 and 25°C (68 and 77°F) respectively for winter and summer. Note that the results give primary heating and cooling loads, with no adjustment made for gas furnace efficiency or COP of the air-conditioning. No seasonal cutout was used; e.g. heating was free to be used in summer although in practice it was not required. In common with typical intermittent usage, heating was used for the period 0700-1000 and 1600-2400 in winter, and cooling from 0700-2400 hours. Additional natural ventilation of 10 air changes/hour was applied in summer when outdoor temperatures were favorable. It should be noted that the vast majority of Australian (and New Zealand) homes do not have whole-house air-conditioning. Many people rely on ventilation, night cooling, shades, etc to limit summer discomfort. However, a small cooling load is an indicator of good summer performance, even if it is hypothetical.

Table 1 shows the seven windows that were analyzed. They vary from a single pane clear unit with a total U-factor of 6.0 W/m^2K (1.1 $Btu/h\text{-}ft^2F$) and solar heat gain coefficient of 0.84 to a highly insulated evacuated double pane window with low-e coating with a U-factor of 0.80 W/m^2k (0.14 $Btu/h\text{-}ft^2F$) and solar heat gain coefficient of 0.53. This vacuum glazing is the subject of IEA Task 18's Project B5, led by Australia. Also simulated was a single pane glazing with solar control laminate and low-e coating with a U-factor of 3.3 W/m^2k (0.58 $Btu/h\text{-}ft^2F$) and solar heat gain coefficient of 0.31. In all cases an appropriate frame type was chosen for each glazing.

The results are shown in Figure 1. Most obvious is that the heating and cooling loads are very climate-dependent. Darwin requires no heating at all but more than twice the cooling energy of Sydney. Canberra's heating loads are about three times those of Sydney which is consistent with their respective heating degree days.

The ranking of the seven windows varies with climate. In the hotter climates the windows with the lowest solar transmittances (shading coefficients) perform the best for cooling and overall. Another frequently-observed trend in cooling loads may be seen: generally, cooling energy increases slightly as the U-factor of the window is reduced. We assume that this is due to stored heat being 'trapped' more by insulating glazing than by less insulating glass. Of course this could be an artifact of the rather rigid simulation methodology which lacks the commonsense of a real human occupant. In the real world, a little additional natural ventilation could reduce the problem.

For Darwin where only cooling matters, the clear 'winner' is window #6. However its visible transmittance of 24% would be too low for many homeowners. There is little point having gloomy interiors which largely negate cooling energy savings because of high lighting loads. Option #2 with a visible transmittance of 54% is a better compromise. An alternative to low-SC glazings is the judicious use of either external shades or reflective internal shades or blinds. However such devices are also extra-cost items which must be included in the total cost of the window system and are beyond the scope of this study.

In Sydney a similar conclusion to Darwin may be drawn - a high-performance spectrally-selective single-glazed design offers considerable heating and cooling load improvements. This points to a large market for glazings with high luminous efficacies and similar high-daylight solar-control films for retrofit applications. These findings are in accord with other studies for cooling-dominated climates, such as Southern California and Florida (Refs. 2, 3). In most cases, high-performance single-pane glazings can be selected for warm-to-hot climates where their good solar rejection is much more beneficial than a very low U-factor.

In Canberra and anywhere cooler [up to 4000HDD to base 18C (7200 HDD base 65F) such as in mountainous areas of the southeast, in most of Tasmania and in the South Island of New Zealand], the lowest U-factor windows yield the best heating results. Cooling-load performance become less important. The passive-solar benefit of high shading coefficient and low U-factor is seen clearly in the Canberra results. Increased thermal mass in zones receiving direct gain would enable such glazings to perform even better.

<u>References</u>

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TABLE 1
Residential Glazing Properties

	GLAZING	SHGC(Tset)	SC	Tvis	U-Factor, Total W/m^2-K (Btu/h-ft^{2}F)
1.	Single (3)	0.84	0.96	0.82	6.00 (1.10)
2.	Single, Tint, 1LE (3LE)	0.31	0.35	0.54	3.30 (0.58)
3.	Double, air (3-12.7-3)	0.66	0.75	0.67	3.50 (0.62)
4.	Double, 1LE, air (3-12.7-LE3)	0.63	0.72	0.63	2.70 (0.48)
5.	Double, 1LE, argon (3-12.7A-LE3)	0.60	0.68	0.63	1.80 (0.32)
6.	Double, Refl, 1LE, air (3RE-12.7-LE3)	0.18	0.21	0.24	2.10 (0.37)
7.	Double, 2LE, vacuum (3-12.7V-LE3)	0.53	0.60	0.57	0.80 (0.14)

DENMARK

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SIMULATION RESULTS: Denmark

This study investigated the energy performance of advanced glazing in typical Danish commercial and residential buildings. We used the TSBI3 hour-by-hour building energy simulation program to analyze the demand for heating and/or cooling and peak load of the heating/cooling system as a function of glazing/frame type, size and orientation. The glazing area of the window was varied for each facade corresponding to 0%, 15%, 30% and 50% of the area of the facade. As climatic data we used the Danish Test Reference Year for Copenhagen. Copenhagen is at the sea at 56N longitude and has a temperate climate. Cooling, especially in residential buildings, is not common due to the temperate climate.

Two types of glazing were used (Table 1): Aerogel (U-value 0.6 W/m2K, solar-transmission 0.76) and Low-E double pane (U-value 1.85 W/m2K, solar-transmission 0.73). The high solar-transmission is due to the use of iron-free glass in both glazing types. As frames we used a traditional frame (U-value 2.2-2.4 W/m2K) and a "super-insulated"-frame (U-value 1.5 W/m2K). Results from the models with Aerogel-glazing were compared to results from the models with Low-E glazing. The general result was that a change in glazing from Low-E to Aerogel would cause a saving in the total energy-demand. Apart from the energy-savings a change from Low-E to Aerogel-glazing will have a positive impact on the indoor climate as the inside surface-temperature of the glazing increases due to the lower U-value. The increase in glazing-temperature reduces radiation-asymmetry during winter-time.

a. Commercial Buildings

(1) Aerogel

<u>Summary:</u>
We simulated one floor of a multistory office building. Our results show that the total energy demand (heating and cooling demand) is strongly dependant on the window-to-wall ratio and the window/frame-type. An increase in window-to-wall ratio causes an increase in total energy demand, when using Low-E glazing. When using Aerogel-glazing it is possible to achieve a lower total energy demand than when using Low-E-glazing. The lowest total energy-demand (combination of heating and cooling demand) when using Aerogel-glazing is found when having a window-to-wall ratio of 15%. Generally the peak load from the heating and cooling system increases if the window area is increased. Changing the glazing-type does not have any severe consequences on the indoor-climate regarding high temperatures.

<u>Discussion</u>
By using TSBI3 to analyze the commercial multistory model, energy-demand for heating and cooling is found. Annual and peak heating and cooling energy requirements were calculated as a function of window type, size and orientation. We simulated two offices and one hallway located in the middle of a multistory building (Figure 1). Each office has a floor area of 15.4 m2. The outer-walls were made of two layers of concrete with insulation between. Windows in the model were facing north and south, but to simulate the east/west-orientation of windows, the model was rotated ninety degrees after the first series of simulations. The heating and cooling system was

controlled by a dual set point thermostat. Heating set point was 21 C from 6am to 5pm with a night setback to 18 C, while the cooling set point was set at 25 C. Cooling system COP was 3.0 and heating efficiency was set to 0.9.

<u>Aerogel vs. Low-E doublepane with conventional frames</u>
Heating demand for the north/south-facing commercial building is shown on Figure 2. A similar Figure for the east/west model could be shown. When substituting Low-E with Aerogel-glazing, savings from 7% (with 15% window-to-wall ratio) to 19% (with 50% window-to-wall ratio) of the annual heating demand become possible. For a typical Danish commercial building, with a 40% window-to-wall ratio, the saving is about 16%.

The largest energy-consumption for cooling, Figure 3 (similar results exist for the east-west-model), is found in the models with the largest and the best insulating windows. The large cooling demand in the models with Aerogel-windows is due to the heating dominated climate. Even when cooling is required the exterior temperature is most often lower than the interior temperature. By using better insulated windows, which makes it harder for the heat to escape from the building, the need for cooling increases. The difference in cooling demand between the two glazing types ranges from 9% (with 15% window-to-wall ratio) to 24% (with 50% window-to-wall ratio). With a typical Danish commercial building, the increase in annual cooling-demand would be about 22% when changing between the two glazing types.

On Figure 4 the total energy demand (heating and cooling) is shown. A similar Figure for the east/west-model could be shown. By substituting Low-E glazing with Aerogel glazing, and not changing the window-frame, it is possible to save up to 17% of the total energy demand in commercial buildings. For a typical Danish commercial building, the typical energy saving would be about 14%. Almost no difference is found when examining the energy demand for lighting in the models with different glazing types, which is due to the small difference in light-transmittance.

Examining the peak load for the heating system, it is found that the highest peak load is found during Monday mornings where the heating system has one hour to increase the indoor temperature by one to three degrees. The term "heating peak load" is therefore not quite correct as the peak load is found when the heating system goes from night-setback to normal set point. The heating peak load is generally highest in the north and eastzone of the building. The difference between the peak load in the north and south zone (as well as the east and west zone) when using a window-to-wall ratio of 0% is due to a difference in the outer wall construction. In these two zones the peak load is almost unchanged despite changes in window-to-wall ratio and glazing-type. In the south- and west-zone the heating peak load varies according to the window-to-wall ratio. When changing from Low-E to Aerogel-glazing in a typical Danish commercial building, it is possible to lower the heating peak load 16% in the north/south model and 3% in the east/westmodel.

The largest variation in peak load for cooling between the examined models with Low-E and Aerogel-glazing is about 3%. The cooling-device is hindered in using more energy because of limitations in air-flow and minimum ventilation air-temperature (higher airflow or lower ventilation air-temperature would result in a bad indoor-climate). This hindrance has an influence on the peak load for the cooling device, which especially affects the models with high-insulating or large windows. The window-to-wall ratio has a significant influence on the cooling peak load, where an increase in window area causes an increase in cooling peak load. In a typical Danish commercial building the cooling peak load is increased by 3% when changing the window-glazing from Low-E to Aerogel.

Due to the lower U-value, the indoor-temperature is sometimes higher in models with Aerogel-glazing than in models with Low-E-glazing. Examining work-hours during the year, it is found that the amount of hours with temperatures above 24 C rises by 10% (15% window-to-wall ratio) to 20% (50% window-to-wall ratio) when changing glazing from Low-E to Aerogel. Due to the power of the cooling-device, temperatures above 25 C are very unusual.

The indoor climate has been examined during four typical days of the Danish Test Reference Year. Comparing indoor-temperatures with window-to-wall ratios at 15%, no difference is found between the models with Low-E and Aerogel-glazing. When using larger window-to-wall ratios (30% and 50%) the temperature-difference between the models is below 1 C during the four examined days. Comparing the models with Low-E and Aerogel-glazing, it is found that the indoor-climate does not suffer, as the increase in temperature-level is so small compared to the general temperature-level.

<u>Aerogel vs. Low-E doublepane with "Superinsulated"-frames</u>
Heating demand for the north/south-facing commercial building is shown on Figure 2. When using Low-E glazing the energy demand increases with the window-to-wall ratio. When using Aerogel-glazing the minimum energy demand is with a window-to-wall ratio of 30%. When substituting the glazing from Low-E to Aerogel, the annual heat demand savings range from 8% (with 15% window to wall ratio) to 23% (with 50% window-to-wall ratio). When changing glazing from Low-E to Aerogel in a typical Danish commercial building, with 40% window-to-wall ratio, the saving would be about 19%.

The largest energy-consumption for cooling is found in the models with the largest and best insulating windows, which can be seen on Figure 3. This is due to the heating-dominated location of the models. Increase in cooling demand, when changing glazing-type, range from 9% (with 15% window-to-wall ratio) to 26% (with 50% window-to-wall ratio). Having a typical Danish commercial building the increase in cooling demand, when changing glazing in the windows and leaving the frames untouched, would be about 21%.

Looking at Figure 4, it is found that it is possible to save up to 19% of the total energy demand (sum of heating and cooling) in commercial buildings with Superinsulated frames by substituting Low-E with Aerogel-glazing. The saving in a typical Danish commercial building, when changing glazing and keeping the Superinsulated frames is about 16%.

Almost no difference in the energydemand for lighting between the models with different glazing types is found, which is due to the small difference in light-transmittance.

Examining the peak load for the heating system, it is found that the load is highest in the north and eastzone of the building. The term "peak load" is, as in the models with conventional frames, not quite correct due to the night-setback of the heating system. The difference between the peak load in the north and south zone (as well as the east and west zone) when using a window-to-wall ratio of 0% is due to a difference in the outer wall construction. In these two zones the peak load is almost unchanged despite changes in the window-to-wall ratio and glazing type. When changing from Low-E to Aerogel-glazing it is possible to lower the heating peak load up to 11% in the north/south-model and 5% in the east/west-model of the total heat peak load, when using 50% window-to-wall ratio. This is also the saving when using a 40% window-to-wall ratio, which is a typical number for Danish commercial buildings.

The largest variation in peak load for cooling between models with Low-E and Aerogel-glazing is about 3%. Like in the models with conventional frames, the cooling device is hindered in using more energy due to some limitations. When comparing results with "Standard"-frames and "Super-insulated" frames, it is seen that the frame-type has almost no influence on the cooling peak load.

Due to the lower U-value the indoor-temperature is sometimes higher in the models with Aerogel-glazing than in the models with Low-E-glazing. When examining the work-hours during the year, it is found that the amount of hours with temperatures above 24 C rises with 10% (window-to-wall ratio = 15%) to 21% (window-to-wall ratio=50%). Due to the power of the cooling-system it is very unusual to have temperatures above 25 C.

The indoor climate has been examined during four typical days of the Danish Test Reference Year. When using small window-to-wall ratios (15%) there is no difference between the models with Low-E and Aerogel-glazing. When using larger window-to-wall ratios (30% and 50%) the temperature-difference between the models is below 1 C during the four examined days.

A consequence of a change in glazing from Low-E to Aerogel is (as mentioned before) that temperature rises in the model. During the year, hours with indoor-temperatures above the heating set point will be more frequent. Due to the cooling device, hours with very high temperatures (above 25 C) will be very uncommon, and is not regarded as being a problem.

TABLE 1

Glazing Solat/Optical/Thermal Properties

Glazing	SHGC(Tset)	SC	Tvis	U-Factor (COG/Total) W/m^2-K (Btu/h-ft^{2}F)
Double, aerogel (4-20-4)	0.76	0.88	0.76	0.60 (0.11)/1.37 (0.24) Conventional 0.60 (0.11)/0.99 (0.17) Superinsulated

Double, 1 LE, air (4-12-LE4)	0.73	0.85	0.73	1.85 (0.33)/2.00 (0.35) Conventional 1.85 (0.33)/1.70 (0.30) Superinsulated

Comments to figures:

Figure 1:
Sectional view of the commercial building. Offices are zone 2 and 8. Hallway is zone 5.

Figure 2:
Annual heating demand for the north-south facing commercial building. LE=Low-E double-pane-windows. AE=Aerogel-windows.

Figure 3:
Annual cooling demand for the north-south facing commercial building. LE=Low-E double-pane-windows. AE=Aerogel-windows.

Figure 4:
Total annual energy-demand for heating and cooling for the north-south facing commercial building. LE=Low-E double-pane windows. AE=Aerogel-windows.

b. Residential Buildings

(1) Aerogel

Summary
A one-family single-story home in Copenhagen, Denmark was simulated. Our results show that the total energy demand (heating) is strongly dependant on the window-to-wall ratio. An increase in window-to-wall ratio equals an increase in total energydemand in the models with Low-E glazing. When using Aerogel-glazing it is possible to achieve a lower total energy demand than when using Low-E-glazing. In the model with Aerogel-glazing the minimum total energy-demand is when using a window-to-wall ratio of 30%. The heating peak load is lowered approx. 13-14 % for a typical Danish residential building, when changing from Low-E to Aerogel-glazing. Changing the glazing-type does not have any severe consequences on the indoor-climate regarding high temperatures.

Discussion
Energy demand for heating is found by analyzing a residential single-story model using TSBI3. Annual and peak heating energy requirements were calculated as a function of window type, size and orientation. Results from the models with Aerogel-glazing were compared to the performance of models with Low-E low-iron glazing.

The residential building consists of one living room, three bed rooms, bath, kitchen and storage room with a net floor area of 83.7 m2. The glazing in the living room and two of the bedrooms are facing south while the glazing in the kitchen and bath are facing north. The last bedroom has glazing facing east, while the storage room has glazing facing west. Size and orientation of the rooms can also be seen on Figure 5. The building was modeled with windows facing north, east, south and west without rotating the model. The outer walls are hollow brick walls with a 0.125 m layer of insulation.

A dual set point thermostat was used to control the heating-system. Heating was set at 20 C with no night setback. Efficiency of the heating system was set at 0.9. No mechanical ventilation is installed in the building; the only type of cooling in the building is ventilation of the building with outside air through window openings. This ventilation starts when the indoor-temperature is above 25 C and is manually controlled.

Aerogel vs. Low-E doublepane with conventional frames
The minimum energy demand, as seen on Figure 6, for heating in the model with Low-E glazing is found when there are no windows in the building. When using Aerogel-glazing the minimum energy demand for heating is with 15% window-to-wall ratio. When substituting low-E windows with Aerogel windows it is possible to save from 13% (with 15% window-to-wall ratio) to 30% (with 50% window-to-wall ratio) of the annual heating demand. As there are no cooling devices in the building this is also the saving-potential for the total energy demand. For a typical Danish residential building, with 25% window-to-wall ratio, the saving potential is 20%.

Almost no difference in the energy demand for lighting between the models with different glazing types is found, which is due to the small difference in light-transmittance.

When changing from Low-E windows to Aerogel windows, the heating peak load is lowered. Reduction in heating peak load is dependant on the window-to-wall ratio and ranges from 9% (15% window-to-wall ratio) to 21% (50% window-to-wall ratio). Most of the reduction in heating peak load comes from the southzone of the building, where the largest window-area is found. For a typical Danish residential building the heating peakload reduction would be about 13%.

In the models, the indoor temperature often exceeds 24 C. In the model with Low-E windows it happens between 1900 hours and 2600 hours during the year depending on the window-to wall ratio. When changing to Aerogel-glazing the temperature exceeds 24 C in 2200 to 3200 hours depending on the window-to-wall ratio. The temperature exceeds 24 C in 1100 hours when there are no windows in the model. For a typical Danish residential building, temperatures above 24 C would be found in approx. 2200 hours for the Low-E model and 25% higher for the Aerogel-model. Because the only means of cooling in the residential building are by airing, indoor temperatures sometimes exceed even higher temperatures. Temperatures above 26 C are found in approx. 20 to 120 hours during the year, depending on the window-to-wall ratio. A change in glazing from Low-E to Aerogel causes only a small increase in the "high-temperature" hours.

The indoor climate has been examined during four typical days of the Danish Test Reference Year. With small window-to-wall ratios (15%) there is no difference between the models with Low-E and Aerogel-glazing. Using larger window-to-wall ratios (30% and 50%) the temperature-difference between the models is below 1.5 C during the four examined days.

<u>Aerogel vs. Low-E doublepane with "Superinsulated"-frames</u>
The minimum energy demand for heating in the model with Aerogel-glazing is found in the model where 30% of the wall area is glazing, as seen on Figure 6. When substituting low-E windows with Aerogel windows, it is possible to save from 15% (with 15% window-to-wall ratio) to 35% (with 50% window-to-wall ratio) of the annual heating demand. As there are no energy consuming cooling devices in the building this is also the saving-potential for the total energy demand. The energy-saving potential in a typical Danish building, with a 25% window-to-wall ratio, is 22%.

Almost no difference in the energy demand for lighting between the models with different glazing types is found, which is due to the small difference in light-transmittance.

When changing from Low-E windows to Aerogel windows, the heating peak load is lowered. The reduction is dependant on the window-to-wall ratio and ranges from 14% (15% window-to-wall ratio) to 23% (50% window-to-wall ratio). Most of the reduction in heating peak load is found to come from the southzone of the building where the largest window-area is found. Changing glazing in a typical Danish building would result in a 14% reduction in heating peak load (same as with 15% window-to-wall ratio).

In the models the indoor temperature often exceeds 24 C. In the model with Low-E windows it happens between 1900 and 2700 hours during the year. When changing to Aerogel windows, the amount of hours is in the interval from 2300 to 3400 hours. The temperature exceeds 24 C in 1100 hours when there are no windows in the model. For a typical Danish residential building the number of hours with temperatures above 24C would be about 2250 for the Low-E model and 2800 for the Aerogel model. For the higher temperatures (above 26) the conclusions are the same as in the models with "Standard frames": the indoor climate does not suffer when changing from Low-E to Aerogel-glazing.

The indoor climate was examined during four typical days of the Danish Test Reference Year. When using small window-to-wall ratios (15%) no difference between the models with Low-E and Aerogel-glazing is found. When using larger window-to-wall ratios (30% and 50%) the temperature-difference between the models is below 1.5 C during the four examined days.

TABLE 2
Savings (in Primary Energy) When Changing
from Low-E Glazing to Aerogel-Glazing
in Commercial and Residential Building

	Window-to-Wall Ratio	Energy Saving (Heating+Cooling) kWh	%	kWh/m2 floor	kWh/m2 window	Peak Load Saving Heating kW	%	Cooling kW	%
Commercial [1]									
Standard	40%	443	14.5	14.4	49.4	0.81	14.5	-0.056	-4.4
Superinsulated	40%	478	16.8	15.5	53.3	0.58	11.0	-0.059	-4.6
Residential [2]									
Standard	25%	1015	19.8	12.1	68.8	0.46	12.8	-	-
Superinsulated	25%	1069	22.1	12.8	72.5	0.48	13.9	-	-

Notes:
1. Only results for the north-south model have been calculated
2. No cooling energy-savings in residential building

In Table 2 the savings when changing glazing type are shown. By changing glazing from Low-E to Aerogel, energy savings at 15-17 % in commercial buildings and 20-22% in residential buildings are possible. In buildings with "Super-insulated" frames the energy savings are larger than when using standard window-frames. The difference between savings in buildings with normal and "Super-insulated" frames is due to a difference in the U-value of normal frames in Low-E and Aerogel-windows.

Savings are also found when looking at the peak load for the heating system. Here the savings range from 11-15% in the commercial building and approx. 12% in the residential building. In the models the better-insulated windows reduce the heat-loss which demands a lower heating peak load. A system which does not benefit from the change of glazing is the cooling system. After a change from Low-E to Aerogel-glazing, the peak load for cooling increases with 5% in the commercial building.

When substituting Low-E- with aerogel-glazing the indoor temperatures are increased a little, especially during summer-time. Comparing the increase in temperature with the temperature-level during summer days, it must be concluded that the glazing-type does not have any severe consequences to the indoor climate regarding high temperatures. During the winter the Aerogel-glazing will have a positive effect on the indoor-climate, compared to the Low-E, as it has a higher surface-temperature due to the lower U-value for the glazing. The increase in the surface-temperature of the glazing reduces the problems with radiation-asymmetry.

Comments to figures:

Figure 5:
Ground plan of the residential building. Zone 1: Living room, Zone 2, 3, 4: Bed-room, Zone 5: Windscreen, Zone 6: Bath, Zone 7: Kitchen, Zone 8: Storage room, Zone 9: Hallway.

Figure 6:
Annual heating demand for the residential building. LE=Low-E double pane-windows. AE=Aerogel-windows.

FINLAND

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SIMULATION RESULTS: Finland

Work in Finland analyzed the performance of electrochromic windows in commercial buildings (Ref. 1) and superinsulated windows in both commercial (Refs. 2, 3, 4) and residential buildings (Refs. 5, 6, 7). Heating and cooling energy demand were calculated for three geographic loactions using the TRNSYS computer program. For the electrochromic study, emphasis was placed on evaluating the energy and daylighting performance of the window using different ccontrol strategies. The analysis of superinsulated windows focused on determining the marginal effects of improving window U-value and total solar energy transmittance. Economic viability calculations were performed for all the studies.

a. Commercial Buildings

(1) Electrochromics

<u>Summary</u>
This study (Ref. 1) investigated the energy performance of the electrochromic window in a typical Finnish office building, located in Helsinki. The TRNSYS simulation program was used to analyse the energy and peak demand effects of a electrochromic window. The electrochromic window properties were selected to describe the typical electrochromic solution. The control of the glazing transmittance was based on the daylight illuminance of the room. The south facade window was selected to find the maximum energy and power investment saving potentials of the electrochromic device. The results showed that the effect of the switchable characteristics of the window on the energy costs is quite small in a Finnish climate and the use of electrochromic windows can not be justified by the energy savings. The use of electrochromic glazings in Finland could be justified by the decrease in the cooling power investment. The case analyses showed that the cooling power investment represents 60-90 % of the sum of the present worth of the energy costs and cooling power investments.

<u>Discussion</u>
The profitability of using electrochromic glazings in a Finnish climate was analysed in the case of the office building. The office building is located in Helsinki. The orientation of the window is to the South, which is assumed to have the biggest profitability in using the electrochromic window. The area of the office building module is 1555 m2. The window to floor area ratio is 0.3. The thermal transmittance of the external wall is 0.30 W/m2K. The office building consists of three types of rooms: meeting rooms, office rooms I (no electric appliances), and office rooms II (microcomputer, 200 W). 33 % of the office rooms are type I and 67 % type II.

The solar and visible transmittance of the electrochromic glazing was controlled continuously between the minimum and maximum values. The control is based on the daylight illuminance in the middle-point of the room. The set value for the room illuminance is 500 lux. The electrochromic glazing was double pane with the following properties:

The total solar energy transmittance of the glazing was controlled between 0.16-0.49 and the visible transmittance between 0.10-0.66. The minimum control signal (0 %) corresponds to the minimum transmittance values and the maximum control signal (100 %) corresponds to the maximum transmittance values. Four different cases were calculated:

1. Window properties constant: U=2.5 W/m2K, Tset=0.49, Tvis=0,66. Continuous lighting 15 W/m2 between 8 AM and 4 PM.
2. Window properties constant: U=2.5 W/m2K, Tset=0.49, Tvis=0,66. Continuous lighting control (dimming) between 8 AM and 4 PM, max 15 W/m2, set point 500 lux.
3. Window solar and visible properties controlled, set point for room illuminance 500 lx. U=2.5 W/m2K, Tset=0.16...0.49, Tvis=0.10...0.66. Continuous lighting 15 W/m2 between 8 AM and 4 PM.
4. Window solar and visible properties controlled, set point for room illuminance 500 lx. U=2.5 W/m2K, Tset=0.16...0.49, Tvis=0.10...0.66. Continuous lighting control (dimming) between 8 AM and 4 PM, max 15 W/m2, set point 500 lx.

The net effect on the energy cost was calculated using the prices: heating energy 0.15 FIM/kWh, cooling energy 0.45 FIM/kWh (for cooling COP=3), and electricity 0.45 FIM/kWh. Figure 1 shows the energy effects of four different window and lighting strategy cases. Comparison between cases 1 and 2 shows the energy saving potentials of lighting control in the office building. Annual internal gains decreased from 72.3 kWh/m2 floor area to 52.4 kWh/m2 (difference -19.9), cooling energy decreased from 38.0 kWh/m2 to 27.6 kWh/m2 (difference -10.4). The heating energy increased from 81.7 kWh/m2 to 89.3 kWh/m2 (difference +7.6). The energy cost difference between cases 1 and 2 is 9.4 FIM/m2.

Cases 1 and 3 show the effect of the control of solar and visible transmittances on the heating and cooling energy consumption. The cooling energy decreased from 38,0 kWh/m2 to 20.5 kWh/m2 (difference -17.5) and the heating energy increased from 81.7 kWh/m2 to 88.9 kWh/m2 (difference +7.2). The energy cost difference between the cases 1 and 3 is 1.5 FIM/m2. The net energy cost difference per window area is 5.2 FIM/m2. Using a window lifetime of 15 years and a discount rate 0 % shows the present worth of the energy cost savings to be 78 FIM/m2.

The maximum cooling load in case 1 is 117.4 kW (75 W/m2) and in case 3 80.1 kW (52 W/m2). The difference between cases 1 and 3 is 37.3 kW, which is 81 W/m2 window area. Using 1300 FIM/kW as the marginal cooling investment price for centralized cooling, gives the cooling investment effect per window area as 105 FIM/m2 window area. If the cooling power is localized, the marginal price is assumed to be 6500 FIM/kW. In that case, the cooling power investment is 527 FIM/m2 window area. The comparison between cases 2 and 4 shows also the effect of the control of the window transmittance on the energy costs and power investments. The difference in that case is lower. The decrease in the cooling power investment gives the main justification for the use of electrochromic glazing is Finnish climate conditions.

References

1. Ismo Heimonen, Economic Viability of Advanced Windows in the Finnish Climate. VTT Building Technology, Building Physics. IEA Report T18/A2A3/FIN1/96, July, 1996.

TABLE 1
Commercial Building Energy Study
Electrochromic Solar/Optical/Thermal Properties

	SHGC (Tset)	SC	Tvis	U-Factor - COG W/m^2-K (Btu/h-ft^{2}F)
	Bleached/ Colored	Bleached/ Colored	Bleached/ Colored	Bleached/ Colored
Electrochromic				
Double, EC, air (6ECA-6.3-6)	0.49/0.16	0.57/0.19	0.66/0.10	2.50 (0.44)/2.50 (0.44)

(2) Superinsulated

Summary

This study investigated (Refs. 2, 3, 4) the effects of different types of superinsulated windows on the energy and peak demand of an office building, located in Helsinki, Finland. The TRNSYS, FRAME, and WINDOW programs were used in the analyses. The analyses were done for typical Finnish windows which have good thermal resistance. However, solar control glazings were also analyzed. The present worth of the energy costs and the heating and cooling power investments were calculated and the differences in the overall costs between the window types are presented. The effects of window orientation, window-to-wall ratio, the level of internal gains, and the building location on the energy consumption is included in the analyses. In summary, in a typical Finnish office building located in Helsinki, the economically profitable marginal additional investment for thermal insulation of an advanced window is 250-330 FIM/m2 window area/(W/m2K) and for solar control is 19-96 FIM/m2 window area/10 % in the total solar energy transmittance.

Discussion

The energy analyses of the office building was done using the window types presented in Table 2. Additional building energy analyses have also been done also in a general way using two parameters (U, Tset) to describe the thermal performance of a window. These analyses show in the general way what the energy effect of improving the thermal and solar transmittances of the windows is in the office building. In the analyses the U-value of the glazing varies 0.6-1.8 W/mwK and the total solar energy transmittance of the glazing varies 0.2-0.8. The U-value of the frame in these analyses is 1.6 W/m2K and the frame area is about 25 % of the window area; therefore, the total U-value of the window varies from 0.85 to 1.75 and the total solar energy transmittance from 0.15 to 0.6.

The typical office building is located in Helsinki, $60^{o}19'$ N, heating degree days (HDD) of 4439 (base temperature 17C), Jyväskylä $62^{o}24'$ N with HDD=4997, and Sodankylä $67^{o}22'$ N with HDD=6312. The floor area of the office building module is 1555 m2 with windows oriented to the north, east, south, and west. Window-to-floor area ratio is varied from 0.15 to 0.45. The thermal transmittance of the external wall is 0.30 W/m2K. The office building consists of three types of rooms: meeting rooms, office rooms I (no electric appliances), and office rooms II (microcomputer, 200 W). 33 % of the office rooms are type I and 67 % type II. The internal gains in the office building are: occupancy 15.7 kWh/m2 floor area, lighting 30.3 kWh/m2 floor area, and electric appliances 27.4 kWh/m2 floor area.

Performance of Selected Window Tyqpes

Building level energy analyses has been done for the types shown on Table 2. Figure 1 presents the energy demand of the office building using different window structures, when the window orientation is North, East, South or West. The cooling demand in the north orientation is below half of the cooling demand in the south orientation. The cooling demand in the east and west facing rooms is between the demands in the north and south room and the west room demand is about 30 % higher than in the east rooms.

General Energy Analyses

A general energy analyses has been done using window U-values 0.85-1.75 W/m2K and total solar energy transmittances 0.15-0.6. These analyses show in a general way what the energy effect is of improving the thermal and solar transmittances of the windows in the office building. In the analyses, the U-value of the glazing varies from 0.60 -1.8 W/m2K and the total solar energy transmittance from 0.20-0.80. The area of window was varied using 15-30-45% of the floor area. In the base case, the window area is 30 % of the floor area. The analyses were done using internal gains 50%, 100% (base case) and 150%. The purpose of the general analyses was to find out the energy and power demand effects of the improvement of the window U-value and Tset-value. These energy and power demand effects of the window selection can be used for the economical analyses to find out the economical viability of the advanced glazings.

Effect of Orientation

Figure 2 shows the power demand as well as the heating and the cooling energy demand of north and south facade zones as a function of the U-value and the solar transmittance of windows. According to Figure 2 some rough conclusions can be drawn. First of all, the solar transmittance of glazings has no influence on the heating power demand which is due to the fact that the sun is not shining during the coldest period (dimensioning condition) of the year. The U-value, in turn, has an important influence on the heating power demand. The change in heating energy demand per unit U-value is more noticeable for a north zone than for a south zone. This is due to higher solar gains of a southern zone.

The solar transmittance of the glazing has, nevertheless, a relatively slight effect on the heating energy demand. The solar transmittance properties of the glazings also have an effect on the cooling power demand and on the cooling energy demand. The effect is significant for a south zone. The U-value of the glazing has no influence on the cooling power demand but does influence the cooling energy demand. This is caused by the fact that the conduction heat flow from inside to outside, which is actually cooling the room spaces, is getting lower as the U-value is getting lower.

The marginal effect of the decreasing the window U-value on the yearly heating energy demand is 113-120 kWh/m2 window area/(W/m2K) for the north facade; 105-115 kWh/m2/(W/m2K) for the east facade; 93-105 kWh/m2/(W/m2K) for the south facade; and 103-113 kWh/m2/(W/m2K) for the west facade. The marginal effect on the cooling energy demand is 26-34 kWh/m2 window area/(W/m2K) for the north facade; 32-48 kWh/m2/(W/m2K) for the east; 45-67 kWh/m2/(W/m2K) for the south; and 36-52 kWh/m2/(W/m2K) for the west. The marginal effect of decreasing the U-value on the maximum heating power is in Helsinki and is about 48 W/m2 window area/(W/m2K). The decrease of the U-value also increases the cooling demand, but the effect is very small; i.e., 2-7 W/m2 window area/(W/m2K), depending on the orientation.

The marginal effect of decreasing the window solar energy transmittance (Tset) on the yearly heating energy demand (heating energy demand is increasing and cooling energy demand is decreasing, when Tset is decreasing) is 6.9-9.4 kWh/m2 window area/(10% in transmittance) for the north facade; 6.5-10.7 kWh/m2/(10%) for the east facade; 7.1-12.0 kWh/m2/(10%) for the South facade; and 6.3-10.5 kWh/m2/(10%) for the west facade. The marginal effect on the cooling energy demand is 16.0-19.5 kWh/m2 window area/(10% in transmittance) for the north facade; 30.2-36.5 kWh/m2/(10%) for the east facade; 50.1-58.9 kWh/m2/(10%) for the south facade; and 40.0-47.3 kWh/m2/(10%) for the west facade. The marginal effect on the heating power can be omitted. The effect on the maximum cooling power is about 13 W/m2/(10% in transmittance) for the north facade, 31 W/m2/(10%) for the east, 36 W/m2/(10%) for the south, and 39 W/m2/(10%) for the west.

<u>Effect of Window Area</u>

Figure 3 presents the effect of the window area (15%, 30%, and 45% of floor area) on the heating and cooling energy demand of the office building in Helsinki. In these analyses the total solar energy transmittance of the window is 0.45. If the energy effect of decreasing the U-value is calculated per unit window area, the variation of window area has quite a small effect on the energy consumption. For the north facade the marginal effect of the U-value on the heating energy consumption varies between 113.5-114.2 kWh/m2 window area/(W/m2K). The same effect on the cooling energy demand is 33.6-34.7 kWh/m2/(W/m2K). For a south facade, the marginal effect is larger; i.e., the marginal effect of U-value on the heating energy consumption is 91.5-96.6 kWh/m2 window area/(W/m2K) and for cooling energy demand is 59.0-69.9 kWh/m2/(W/m2K).

<u>Effect of Building Location</u>

The effect of the building location on the energy consumption of the different windows was analysed in three cities: Helsinki (60^{o}19' N), Jyväskylä (62^{o}24' N), and Sodankylä (67^{o}22' N). In Northern Finland, the improvement of U-value becomes more advantageous. For the north-facing window, the marginal effect of decreasing of the U-value on the heating energy is 119 kWh/m2 window area/(W/m2K) in Helsinki, 135 kWh/m2/(W/m2K) in Jyväskylä, and 168 kWh/m2/(W/m2K) in Sodankylä . For a south-facing window, the values are 105, 124 and 157 kWh/window m2/(W/m2K), respectively. For a south-facing window, the marginal effect of decreasing the total solar energy transmittance on the cooling energy is about 50-59 kWh/window m2/(10% in transmittance) in Helsinki, 41-50 kWh/m2/(10%) in Jyvä skylä and 28-37 kWh/m2/(10%) in Sodankylä . For north-facing, the values are 16-19, 14-18 and 7-11 kWh/m2/(10%), respectively.

<u>Effect of Internal Gains</u>

The effects of internal gains on the energy consumption of the different windows were analysed using three levels in internal gains: 50%, 100% and 150%. For the base case (100%), the internal gains are 72 kWh/m2 floor area. Tables 2 and 3 present the marginal effects of decreasing the U-value and Tset-value of the window on the heating and cooling energy consumption. The results show that the higher level of internal gains in the office building decreases the effect improving the U-value has on heating energy consumption. The improvement in thermal insulation of the window becomes less economical. Decreasing the Tset-value becomes more economical, when the level of internal gains is increasing.

<u>Economic Viability</u>

The Present worth method was used to compare the economical effects of changing the U-value and Tset-value of the windows. The price of the heating energy is 0.15 FIM/kWh, cooling energy

0.45 FIM/kWh with a COP=3.0. The analyses also included the effect of the power investment on the profitability of improvement of the window. The marginal price is 1300 FIM/kW for the cooling power investment (marginal price for centralized cooling) and 600 FIM/kW for heating power investment. The annual price of the heating power is 125 FIM/kW per m2 floor area. The discount rate is assumed to be 0% and window lifetime 15 years (20 years, 3% and 30 years, 5% gives the same result). Figure 4 shows the marginal profitability of improving (decreasing) the U-value in the office building located in Helsinki. It is a function of orientation and varies between 250 - 330 FIM per unit of U-value. Figure 5 shows the marginal profitability of decreasing of Tset-value. It varies between 19-96 FIM/10% in solar energy transmittance. Solar protection is the most economical for the South facade. In this context, profitability means that the additional investment of the advanced windows compared to the reference case could be the amount mentioned.

Usually decreasing the U-value of a window also affects the solar energy transmittance. Figure 6 shows the differences in the present worth of the energy cost and power investment of the different window types for the office building located in Helsinki . The reference case is the window #1b (double clear low-e, wooden frame, fixed window). The additional investment for window #5b is about 500 FIM/m2 window area if the window orientation is south or west. For the east facade, the additional investment is about 410 FIM/m2 and for the north facade about 300 FIM/m2. The improvement of the window is more economical in Jyväskylä and Sodankylä than in Helsinki.

<u>References</u>

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3. Heimonen, I., Hemmil‰, K. & Saarni R. Development of the Future Building Window. Research report DRAFT, in Finnish.

4. Virtanen, M. & Heimonen, I. Examples of Advanced Glazing Applications in Cold Climate. World Renewable Energy Congress, 15-21 June, 1996. Denver, Colorado, USA. Pages 523-530.

TABLE 2
Commercial Building Energy Study
Superinsulated Solar/Optical/Thermal Properties

	SHGC (Tset)	SC	TVIS	U-Factor - COG/Total W/m^2-K (Btu/h-ft^{2}F)
1b. Double, 1LE, air (6-12.7-LE6)	0.76	0.88	0.77	1.74 (0.58)/1.93 (0.34)
2. Triple, air (6-12.7-6-12.7-6)	0.71	0.83	0.76	1.86 (0.33)/1.80 (0.32)
3. Triple, 1LE , air	0.68	0.79	0.71	1.38 (0.24)/1.47 (0.26)

	(6-12.7-6-12.7-LE6)				
5b.	Triple, HM66, argon (6-12.7A-LE6-12.7A-HM-6)	0.40	0.46	0.51	1.17 (0.21)/1.33 (0.23)
9.	Triple, 1LE, ASUN, argon (6-12.7A-LE6-12.7A-ASUN6)	0.44	0.51	0.59	1.20 (0.21)/1.35 (0.24)

TABLE 3

Marginal Effect of Decreasing the Window U-Value on the on Heating and Cooling Energy Consumption in Helsinki (Tset=0.30, 100% Level Internal Gains)

Orientation	Level of the internal gains	The effect on the heating energy consumption $kWh/m^2/(W/m^2K)$	The effect on the cooling energy consumption $kWh/m^2/(W/m^2K)$
North	50 %	125.8	-18.2
	100	119.8	-25.8
	150	110.1	-35.8
South	50 %	113.5	-34.3
	100	104.5	-45.3
	150	95.6	-56.2
East	50 %	122.7	-25.1
	100	115.2	-32.4
	150	105.2	-43.5
West	50 %	121.1	-28.2
	100	113.0	-35.7
	150	103.1	-46.6

TABLE 4

Marginal Effect of Decreasing the Window Tset-Value on the on Heating and Cooling Energy Consumption in Helsinki (U-value=0.85 W/m2K, 100% Level Internal Gains)

Orientation	Level of the internal gains	The effect on the heating energy consumption kWh/m^2/(10 %)	The effect on the cooling energy consumption kWh/m^2/(10 %)
North	50 %	-9.3	17.4
	100	-6.9	19.5
	150	-4.8	22.1
South	50 %	-10.1	55.0
	100	-7.2	58.9
	150	-5.0	62.0
East	50 %	-9.6	32.4
	100	-6.5	36.6
	150	-4.7	39.2
West	50 %	-9.1	43.4
	100	-6.3	47.3
	150	-4.5	49.9

a. Residential Buildings

(1) Superinsulated

Summary

This study investigated (Refs. 5, 6, 7) the effects of different types of windows on the energy and peak demand of a residential building, located in Finland. TRNSYS, FRAME and WINDOW-programs were used in the analyses. The case analyses were done for typical Finnish windows with a good thermal resistance. The general values for the energy effects of decreasing of the U-value and the total solar energy transmittance (Tset) of the windows in office building have been presented. The present worth of the energy costs were calculated and the differences in the energy costs between the window types has been presented. The effects of the building location on the energy consumption have been included in the analyses. As a summary, in a typical Finnish office building located in Helsinki, the economically profitable marginal additional investment for a thermal insulation of the advanced window is 410-450 FIM/m2 window area/(W/m2K). Usually improving the thermal resistance affects on the solar energy transmittance thus negating the benefits associated with lower U-value. The negative effect of the decrease in the total solar energy transmittance of the window is about 72-78 FIM/m2 window area/10% in the total solar energy transmittance. The use of highly insulated windows is getting more economical in the Northern part of Finland, naturally.

Discussion

The energy analyses of the residential building case were completed for the Finnish window types presented in Table 5. Additional building energy analyses have also been done also in a general way using two parameters (U, Tset) to describe the thermal performance of a window. These analyses show in the general way what the energy effect of improving the thermal and solar transmittances of the windows is in the office building. In the analyses the U-value of the glazing varies 0.6-1.8 W/mwK and the total solar energy transmittance of the glazing varies 0.2-0.8. The U-value of the frame in these analyses is 1.6 W/m2K and the frame area is about 27 % of the window area; therefore, the total U-value of the window varies from 0.87 to 1.75 and the total solar energy transmittance from 0.15 to 0.59.

The typical Finnish residential building is located in Helsinki, 60°19' north latitude with heating degree days (HDD) of 4439 (base temperature 17C), Jyväskylä, 62°24' N with HDD=4997, and Sodankylä 67°22' N with HDD=6312. Total floor area of the building is 134 m2. Windows are distributed as follows: North 1.44 m2, East 3.24 m2, South 7.92 m2, and West 1.8 m2. There is and 2.7 m2 glazings in doors facing south. Internal gains are: occupancy 11.2 kWh/m2 floor area, electric appliances 12.0 kWh/m2, and lighting 8.6 kWh/m2.

Heating Energy Performance

Figure 1 shows what the effect of total U-value and solar energy transmittance for different windows on the heating energy demand in a residential building located in Helsinki. If the difference in heating energy demand per window area (17.1 m2) is divided by the difference in window U-values, we will get a general result; i.e., the energy effect of improving (decreasing) the U-value of the window in Helsinki is 115-127 kWh/m2 window area/(W/2K). The energy effect of the increasing the total solar energy transmittance of the window is 21-22 kWh/m2 window area/(10% in transmittance). Changing window #1b (U=1.93, Tset=0.57) to window #6b (U=1.18, Tset=0.43) results in a heating energy decrease of 7.7 kWh/m2 floor area in Helsinki; i.e. [(1.93-1.18)*121-(0.57-0.43)*21.5/0.1=60.6 kWh/m2 window area = 7.7 kWh/floor m2].

Effect of Building Location

Figure 2 shows he effect of climate on heating energy demand of the residential building. Data is presented for Helsinki, Jyväskylä and Sodankylä. The energy effect of the improving (i.e., decreasing) the U-value of the window is 115-124 kWh/m2 window area/(W/m2K) in Helsinki, 131-139 kWh/m2/(W/m2K) in Jyväskylä and 167-173 kWh/m2/(W/m2K) in Sodankylä. The energy effect of the increasing the total solar energy transmittance of the window is about 20.5 kWh/m2 window area/(10% in transmittance) in Helsinki, 19.6 kWh/m2/(10%) in Jyväskylä and 21.4 kWh/m2/(10%) in Sodankylä. Changing window #1b (U=1.93, Tset=0.57) to window #6b (U=1.18, Tset=0.43) results in a heating energy decrease of 60 kWh/m2 window area in Helsinki, 74 kWh/m2 in Jyväskylä and 97 kWh/m2 in Sodankylä.

Economic Viability

The economics analyses was based on the Present Worth Method using an energy price 0.30 FIM/kWh (1 ECU=5.9 FIM, 1 US$=4.9 FIM), discount rate 0.07 and a window lifetime 25 years. The Present Worth of the marginal heating energy cost saving in the residential building in Helsinki is about 410-450 FIM/m2 window area per U-value unit in area for U-values 0.9-1.8 W/m2K (using the energy price of 0.30 FIM/kWh, discount rate 0,07 and window lifetime 25 years). The economically viable additional investment for improving (decreasing) the U-value could be the amount mentioned above. Usually when improving the U-value the total solar energy transmittance decreases which leads to lower solar heat gains in the building thus negating the benefits of the lower U-value. The present worth of the marginal heating energy cost increases by 72-78 FIM/(10% in total solar energy transmittance) when decreasing the Tset-value. Changing window #1b (U=1.93, Tset=0.57) to window #6b (U=1.18, Tset=0.43) results in a heating energy cost decrease of (1.93-1.18)*430-(0.57-0.43)*75/0.1=218 FIM/m2 window area in Helsinki.

When the U-value decreases, the marginal energy cost saving (and also the economical additional window investment) decreases. The improvement in window U-value is more economical in Northern than in Southern Finland, naturally. The Present Worth of the marginal heating energy cost saving when improving the U-value of the window is about 430 FIM/m2 window area per U-value unit in Helsinki, 490 FIM/m2 per U-value unit in Jyväskylä and 610 FIM/m2 per U-value unit in Sodankylä (energy price 0.30 FIM/kWh, discount rate 0,07 and window lifetime 25 years). The present worth of the marginal heating energy cost decreases by 72 FIM/(10% in total solar energy transmittance) in Helsinki, 68 FIM/(10% in total solar energy transmittance) in Jyväskylä and 75 FIM/(10% in total solar energy transmittance) in Sodankylä when decreasing the Tset-value. These numbers are rough estimates when the window U-value is between 0.9-1.8 W/m2K and Tset between 0.15-0.6.

Using the marginal energy costs obtained from the general analyses, changing window #1b window (U=1.93, Tset=0.57) to window #6b (U=1.18, Tset=0.43) results in a heating energy cost decrease of 220 FIM/m2 window area in Helsinki, 270 FIM/m2 in Jyväskylä and 350 FIM/m2 in Sodankylä. Table 3 presents additional economical investments for different type of windows compared to reference case.

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TABLE 5
Residential Building Energy Study
Superinsulated Solar/Optical/Thermal Properties

		SHGC (Tset)	SC	TVIS	U-Factor - COG/Total W/m^2-K (Btu/h-ft^{2}F)
1b.	Double, 1LE, air (6-12.7-LE6)	0.76	0.88	0.77	1.74 (0.58)/1.93 (0.34)
2.	Triple , air (6-12.7-6-12.7-6)	0.71	0.83	0.76	1.86 (0.33)/1.80 (0.32)
3.	Triple, 1LE, air (6-12.7-6-12.7-LE6)	0.68	0.79	0.71	1.38 (0.24)/1.47 (0.26)
6b.	Triple, 1LE, HM88, argon (6-12.7A-LE6-12.7A-HM-6)	0.57	0.66	0.64	0.94 (0.17)/1.18 (0.21)

TABLE 6
Additional Economical Investments for Different Windows
Using Window #1b as a Reference
(Heating energy price 0.30 FIM/kWh, discount rate 0.07 and window lifetime 25 years)

		Total Window		Energy Cost Difference Compared to case 1b, (FIM/window m2)		
		SHGC (Tset)	U-Factor W/m^2-K	Helsinki	Jyväskylä	Sodankylä
1b.	Double, 1LE, air (6-12.7-LE6)	0.57	1.93 (0.34)	0.0	0.0	0.0
2.	Triple , air (6-12.7-6-12.7-6)	0.53	1.80 (0.32)	-28.9	-38.2	-51.2
3.	Triple, 1LE, air (6-12.7-6-12.7-LE6)	0.51	1.47 (0.26)	-154.6	-184.6	-235.6
6b.	Triple, 1LE, HM88, argon (6-12.7A-LE6-12.7A-HM-6)	0.43	1.18 (0.21)	-219.9	-270.6	-350.6

GERMANY

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SIMULATION RESULTS: Germany

The German work compared the effect of thermotropic glazing with more conventional conventional glazing in the skylight of a residential window. The thermotropic material has a high transmittance at room temperature and a high diffuse reflectance at higher temperatures. Reversible mixing and separation at the molecular level of the material components affects the amount and direction of light scattered by the material, resulting in varying transmittance. The temperature at which these processes occur is determined by the material composition, so it can be selected before manufacture, but cannot be changed afterwards. Thus, it is desirable to determine the optimal switching temperature for a given application, which gives the best combination of high transmittance when solar gains are welcome, to reduce the heating load, and low transmittance when overheating would otherwise be a problem. A quantitative measure for the "optimal switching temperature" is that it minimizes the total cooling and heating load for a building which includes a thermotropic element.

Discussion

The sample building is a two-storey, low-energy house with a total floor area of 200 m2. Without the skylight, it has an annual heating energy consumption of 52 kWh/m2 of residential floor area. The heating profile corresponded to residential use, with 20C guaranteed between 7 am and 10 pm, and 16C during the night. Internal heat sources of 3.35 W/m2 of heated residential area were included. The air exchange rate varied linearly with the season from 0.8 air-changes/hr in winter to 1.5 in summer. Cooling energy was input to ensure a maximum temperature of 26C. This energy can alternatively be interpreted as a measure for the overheating which would occur if active cooling were not applied. Both "heating" and "cooling" energy refer to the final useful energy or load, so do not take equipment conversion efficiencies into account.

The dynamic building simulation program TRNSYS and meteorological data from the Test Reference Years for Freiburg and Bremerhaven were used. Table 1 lists the properties of the glazing types examined. The thermotropic glazing types are characterized by two sets of values, corresponding to the clear and scattering states at room temperature and 50C respectively. To compare the different types of glazing, the minimum total heating and cooling load was determined for each type and is presented in Table 2 and Figures 1 and 2. The tabulated cooling load is a measure of the success of the glazing in preventing overheating.

An important result is that the total heating and cooling load for the thermotropic glazing is lower than for the static glazing and opaque roofing material, for all the parameter variations considered and at both locations. This applies not only when the optimum switching temperature is chosen, but also when a temperature which is several degrees different from the optimum is modelled. It is noteworthy that inclusion of the thermotropic glazing in the insulating window is advantageous even in the cooler climate of Bremerhaven, where overheating occurs less frequently than in Freiburg but is still present.

The effect of varying the area as compared to the reference thermotropic skylight (no. 1) depends on the location. Increasing the area from 8 to 16 m2 (no. 2) is advantageous in Bremerhaven, as the increased solar gains during the heating season outweigh the effect of the increased cooling load in summer, but the situation is reversed in Freiburg. Because the cooling load is higher in Freiburg, the effect of increasing the transmittance in the scattering (blocking) state (no. 4) increases the total load more significantly there than in Bremerhaven. Varying the other parameters has a similar effect in Freiburg as in Bremerhaven, with the values between the two locations differing by a constant offset essentially due to the higher heating load in Bremerhaven. As could be expected, increasing the U-value (no. 3) is disadvantageous both during the heating and the cooling seasons. Conversely, decreasing the absorption in the system, by using low-iron instead of float glass (no. 5), is beneficial in both locations, as then both the transmittance in the clear state and the reflectance in the scattering state are higher. Figures 1 and 2 summarise these results for the thermotropic glazing. The climatic difference between the two locations affects the relative performance of the static glazing. Solar control glazing performs better in Freiburg for this skylight application, whereas heat mirror (low-e) glazing is more appropriate for Bremerhaven. However, the most suitable static glazing for each location is still outperformed by the self-adapting thermotropic glazing. Finally, simple double glazing is seen to be inappropriate for these locations, with high heat losses in winter due to the high U-value and overheating in summer due to the high solar transmittance.

The energy values listed in Table 2 are the simulated building loads. The relationship between these values and the corresponding values for primary energy consumption depends on the combination of primary energy sources and conversion factors typical for a given country. Appropriate values can be estimated from the distributions and conversion values in a national energy flow diagram. Making some reasonable assumptions (e.g. that in private households, all mechanical energy and lighting is powered by electricity), a conversion factor of 0.61 (heating energy consumption: primary energy) is obtained for space heating in German households (values from 1991). Assuming electric-powered, window-mounted air-conditioners with a COP of 2.5, the corresponding conversion factor for room cooling is 0.85. The columns for heating and cooling loads in Table 2 can be divided by these factors to obtain an estimate of the effects on the primary energy consumption. However, as already stated, these primary energy values are determined predominantly by the specific national energy situation. Furthermore, as the factors of 0.61 and 0.85 are of the same order of magnitude while the simulated building energy loads are dominated by heating, consideration of the primary energy instead of the loads would not change the conclusions drawn in the discussion above.
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The total heating and cooling load for the thermotropic glazing is 10% to 20% lower than for static glazing for all the parameter variations considered and at both locations. A slight further reduction in the load obtained with the reference thermotropic skylight can be achieved by reducing the absorption in the system, or by increasing the glazed area at the cooler location. However, the major improvement as compared to static glazing is evident in all the thermotropic variants, due to their characteristic of adapting the transmittance and reflectance to the prevailing climatic conditions.

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TABLE 1
Glazing Properties

	SHGC(Tset)	SC	Tvis	U-Factor (COG) W/m2-K (Btu/h-ft2F)
Thermotropic	Clear/ Scattered	Clear/ Scattered	Clear/ Scattered	Clear/ Scattered
#1 Triple, Thermotropic,1LE, argon (3-1.5TH-3-14A-LE8)	0.52/0.12	0.60/0.14	0.70/0.06	1.24 (0.22)/1.24 (0.22)
#2 Triple, Thermotropic,1LE, argon (3-1.5TH-3-14A-LE8)	0.52/0.12	0.60/0.14	0.70/0.06	1.24 (0.22)/1.24 (0.22)
#3 Triple, Thermotropic,1LE, argon (3-1.5TH-3-14A-LE8)	0.52/0.14	0.60/0.16	0.70/0.06	1.54 (0.27)/1.54 (0.27)
#4 Triple, Thermotropic,1LE, argon (3-1.5TH-3-14A-LE8)	0.52/0.25	0.60/0.29	0.70/0.30	1.24 (0.22)/1.24 (0.22)
#5 Triple, Thermotropic,1LE, argon (3-1.5TH-3-14A-LE8)	0.54/0.11	0.63/0.13	0.70/0.09	1.24 (0.22)/1.24 (0.22)
Conventional				
Double, 1LE, argon (4-16A-LE4)	0.57	0.66	0.76	1.10 (0.19)
Double, Solar #1, argon (6T-16A-4)	0.32	0.37	0.64	1.10 (0.19)
Double, Solar #2, argon (6T-16A-4)	0.10	0.12	0.18	1.10 (0.19)
Double, air (4-14-4)	0.76	0.88	0.82	2.78 (0.49)

Notes:
(1) All window areas are 8m2 except thermotropic # 2 which is 16m2.

TABLE 2
Annual Total, Heating, and Cooling Loads

Freiburg

	Optimum Switching	Total Load (MJ/m2)	Heating Load (MJ/m2)	Cooling Load (MJ/m2)	Max. T (No Cooling)
Thermotropic					
#1	23	152	140	12	31.5
#2	21	155	134	21	32.9
#3	23	157	144	13	31.7
#4	23	158	139	19	32.6
#5	20	149	138	11	31.3
Conventional					
Double, 1LE, argon	-	177	133	44	36.1
Double, Solar #1, argon	-	169	147	22	33.3
Double, Solar #2, argon	-	170	158	11	31.4
Double, air	-	203	150	53	37.3
Opaque Roof	-	159	154	6	29.9

Bremerhaven

	Optimum Switching	Total Load (MJ/m2)	Heating Load (MJ/m2)	Cooling Load (MJ/m2)	Max. T (No Cooling)
Thermotropic					
#1	25	170	167	3	30.4
#2	22	168	161	7	32.0
#3	25	175	172	3	30.6
#4	24	172	167	5	31.6
#5	21	167	165	2	30.1
Conventional					
Double, 1LE, argon	-	181	161	20	35.2
Double, Solar #1, argon	-	183	176	7	32.2
Double, Solar #2, argon	-	191	189	2	30.0
Double, air	-	206	181	26	36.5
Opaque Roof	-	184	183	1	28.6

ITALY

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SIMULATION RESULTS: Italy

An analysis of the energy performance of a typical Italian commercial building equipped with an innovative glazing system was performed using the TRNSYS simulation program. The study was focused on determining the best window-to-wall area ratio for several glazing units and also on determining the most appropriate control strategy for prototypical electrochromic windows. Preliminary work was conducted in order to improve the TRNSYS computer code to facilitate control of the electrochromic windows. A link was established between the output library of the WINDOW 4.0 program and TRNSYS. Electrochromic glazing systems were simulated by an additional routine capable of adopting different control strategies using one or more control parameters. Finally, a subprogram for the calculation of the lighting quantities (daylighting factor and electrical consumption for artificial lighting) was linked to the main program for a complete analysis of the energy performance of the building.

Discussion

Preliminary work was conducted on the TRNSYS computer code to improve the window and glazing components management (Figure 1). A link was established between the output library of the WINDOW4.0 program and TRNSYS. In this way, accurate results computed by a specialised tool was used to calculate the solar gain, heat loss and daylighting characteristics. The control of smart windows (electrochromic glazing systems) was simulated by an additional routine capable of using different control strategies with one or more control parameters. Finally, a subprogram to calculate the lighting quantities (daylighting factor and electrical consumption for artificial lighting) was linked to the main program for a complete analysis of the energy performance of the building.

The examined building shown on Figure 2 was a multistory office building oriented along the east-west direction. On each floor were 20 office spaces each 3.0m x 4.5m; ten facing the south and ten facing the north. The building was located in two different Italian climatic zones: Milano, in the northern part of the country (45.75N) characterised by cold winters and hot and humid summers, and Roma in a Mediterranean zone (41.78N) with mild winters and hot and humid summers. The boundary conditions used for the simulations were the following: internal temperature set-point 20C-26C; employers or clerks presence of 30 persons/floor (equivalent to a mean of 1.5 persons /office) during working days; electrical power of artificial lighting system 180W/office; electrical power of computer, printers, copiers etc. 200W/office; air exchange rate 1 volume/hour.

Six different glazing systems presented on Table 1were examined: two conventional double glazed units (double pane clear, #2614 and double pane low-e tinted with a spectrally selective coating, #2667); two electrochromic units with*"real'* characteristics, #3029 and #3030 and two with*"ideal"* properties, #3041 and #3043. Regarding the control strategies adopted to switch the electrochromic windows, we tested seven different strategies using three types of algorithms. The seven strategies included room temperature, daylight illuminance, incident solar radiation, transmitted solar radiation, room temperature and daylight illuminance, room temperature and incident solar radiation, and room temperature and transmitted solar radiation.

The three algorithms included: proportional control with a status variable using an index between 0-1 to represent how much the electrochromic window was colored; a feedback controller, Figure 3, in which the window properties are adjusted so that the control parameter, at the end of an adjusting loop, is included in a narrow range (this kind of approach is suitable for such parameters as transmitted power or light illuminance that can immediately react with respect to a change in the window properties); and another feedback controller, Figure 4, in which was added a second control variable functioning as a threshold parameter (i.e., if the threshold parameter is over a fixed set-point, the feedback control strategy is activated, otherwise the electrochromic window is completely bleached).

As shown in Figure 5 the heating peak load is a rising function of the windows size. The north-facing results are not significantly different for the glazing units simulated, while some differences appear for south-facing. In fact, the #2667 unit, having the lowest solar energy transmittance, results in the highest heating peak load (about 12% more than the other units in Roma and 7% in Milano for 60% window area).

The cooling peak power, Figure 6, of the clear static unit, #2614, is large for medium and large glazing areas. The required power of the cooling system is doubled using this kind of window facing south; for windows facing north, the factor is about 1.5. The static tinted window, #2667, performs almost as well as the elctrochromic units. However, for south-facing windows, the benefit of using smart windows is evident (about 20% decrease in peak cooling load for the largest window area). It is also evident that the smart glazing units, because of their adaptability, seem to be preferable. The largest advantages are in comparison to the #2614 unit.

The total energy consumption, in the different situations, is summarized in Figure 7. The results show that the energy benefits of static windows, in terms of reducing heating loads of the #2614 glazing unit, are exceeded by the large cooling energy requirements. This is evident for Roma where, for the 60% window area, the total loads are doubled using the #2614 unit, but it is also true for Milano even though it is heating-dominated. For the maximum glazed area, the primary consumption of the clear unit is 34% and 14% larger than the #2667 tinted window (for south- and north-facing windows respectively).   Another important aspect is that with the tinted unit, #2667, it is possible in both orientations and locations to use larger glazed areas without much energy performance degradation.

For the smart windows, the best results occur with the 3043-3044 unit; but the differences with the other electrochromic units are limited. Globally speaking, the minimum energy consumption was achieved using a 3043-3044 unit with a 60% glazed area in Roma and with a 40% glazed area in Milano. It is worth noting that the difference between the largest and medium sized window area in Milano, in terms of annual primary energy consumption, is very small, i.e., 0.4% and 3.8%.
Figure 8 shows a comparison between the best static window (glazing unit #2667 based on the results of our calculation) and the best chromogenic window. The differences are significant for south-facing (26%) and not necessarily negligible for north-facing (about 10%).

Regarding the choice of the switching strategy, we compared the annual total energy consumption using seven different approaches. The graphs in Figure 9 show these results. The influence of control strategy on the annual energy loads is not negligible and the potential energy savings related to the use of smart windows could be substantially reduced using a control strategy not fine tuned. Generally speaking, the best solution seems to be a multi-parameter logic, i.e., daylighting control and room temperature threshold; but it is also one of the more complex strategies. On the other hand, the simplest and easiest to install control systems, i.e., ones based on external sensors, appear to not result in much energy savings. The design of an efficient control system is a critical point when dealing with chromogenic materials, due to control system sensitivity to many factors: the control algorithm, the control parameter, the HVAC interaction, the chromogenic material properties, etc., and only fine tuning can avoid poor performance.

Conclusions

Regarding the conventional selective double glazing #2667, it is preferred in both locations and both north and south orientations because of the large cooling loads. The electrochromic windows always perform better than the conventional windows with a weighted average energy saving of 13.6%. The window-to-wall area ratio that leads to the best performance is 40% for the #2667 for both locations; for electrochromic window #3043-3044, the best window-to-wall ratio is 60% for Roma and 40% for Milano.

The performance of the electrochromic windows can be highly compromised if the control strategy is not well tuned. A simple control logic, i.e., based on external sensors, should be used with care; on the other hand, the best performing control strategies are in general more complex involving two control parameters and not simple algorithms. The control strategy to use must be fine tuned *"on site"* ; i.e., considering the actual HVAC, electrochromic, and building characteristics.

TABLE 1
Commercial Building Energy Study
Electrochromic Solar/Optical/Thermal Properties

	SHGC(Tset)	SC	Tvis	U-Factor - COG W/m^2-K (Btu/h-ft^2F)
	Bleached/ Colored	Bleached/ Colored	Bleached/ Colored	Bleached/ Colored
Electrochromic				
3029-3031				

Double, EC, 1LE, air (6EC-6.3-LE6)	0.56/0.15	0.65/0.17	0.55/0.07	2.40 (0.42)/2.40 (0.42)
3030-3032 Double, EC, 1SS, air (6EC-6.3-SS6)	0.45/0.13	0.52/0.15	0.55/0.07	2.40 (0.42)/2.40 (0.42)
3041-3042 Double, EC, 1LE, air (6EC-6.3-LE6)	0.56/0.10	0.65/0.12	0.56/0.05	2.40 (0.42)/2.40 (0.42)
3043-3044 Double, EC, 1LE, air (6EC-6.3-LE6)	0.56/0.03	0.65/0.03	0.56/0.00	2.40 (0.42)/2.40 (0.42)
<u>Conventional</u>				
2614 Double, air (6-12.7-6)	0.58	0.67	0.62	2.40 (0.42)
2667 Double, Tint, 1LE, air (6LE-12.7-6)	0.25	0.29	0.34	2.10 (0.37)

NORWAY

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SIMULATION RESULTS: Norway

Work in Norway has focused on electrochromic window performance in commercial buildings and high performance insulated glazings in residential buildings at high latitudes. Parametric studies were carried out for locations in Oslo at 59.9N latitude and Tromsø at 69.7N latitude. The TRNSYS hour-by-hour energy analysis simulation program was used for the analyses.

a. Commercial Buildings

(1) Electrochromics

Summary
Building energy simulations were carried out to evaluate the annual energy load and peak demand of a prototypical commercial office building module. For the hour-by-hour energy simulations, the computer program TRNSYS was used. The building was simulated using hourly meteorological data for Oslo (latitude 60_N) and Tromsø (latitude 69_N).

Discussion
The prototypical office building module consists of a 49.7 m2 rectangular core zone (corridor) surrounded by four perimeter zones. Two of the perimeter zones are divided into 9 office spaces of equal size (2.4 x 4.0 m). The other two perimeter zones are assumed to be larger meeting rooms (4.6 x 11.6 m). The floor-to-ceiling height is 2.6 m. The entire office floor is located in a multi-storey building, with similar floors above and below. The offices, meeting rooms and the corridor zone are heated to 22_C during occupied hours (8 am to 5 pm, weekdays) and to 17_C during night and weekends. Cooling is applied to keep the temperature at a maximum of 26_C during the same occupied periods. Ventilation is turned off during nights and weekends.

Insulation and ventilation levels were simulated in accordance with an upcoming new building code
with an exterior wall U-value equal to 0.19 W/m2K, a ventilation rate of 2.97 ACH, and an infiltration rate of 0.15 ACH. A ventilation air heat recovery system with an efficiency of 70% was applied. The internal gains were set in accordance to Norwegian Standard 3031, which give the following values: Lighting: 12 W/m2; Equipment: 4 W/m2; and Occupancy: 4 W/m2.

We analyzed the performance of an absorptive electrochromic window with the solar/optical/ thermal properties shown on Table 1. Electrochromic control strategies analyzed are presented on Table 2 and include no control, incident solar radiation control, and indoor air temperature control. First, a pre-study was performed to select the optimal control strategy. For this initial study, we used Oslo as the location with a window-to-wall ratio fixed at 0.30.

The results are shown in Figures 1 and 2. The temperature control gives the lowest total energy consumption and the lowest peak demand. Other variations of the incident radiation control strategy were also applied, but did not give any lower number and only small variations in the total yearly load and demand. The radiation control strategy gives about 10% reduction in peak demand and about 7% reduction in total energy consumption. The temperature control gives about 15% reduction in peak demand and about 19% reduction in in total energy consumption. Thus, the temperature control strategy #1 (see Table 2) was chosen for the parameter study presented on Figures 3 and 4.

These figures show that the electrochromic windows are most useful for larger window areas. For the building located in Oslo, the reduction in total energy load ranges from 6% for the smallest window area to 25% for the largest window area. For the Tromsø location, the electrochromic window is not very useful because the cooling load is very small. For this building, there is only a small reduction in the total load for the two largest window areas (4-7%).

TABLE 1
Commercial Building Energy Study
Electrochromic Solar/Optical/Thermal Properties

	SHGC(Tset)	SC	Tvis	U-Factor - COG W/m^2-K (Btu/h-ft^{2}F)
	Bleached/ Colored	Bleached/ Colored	Bleached/ Colored	Bleached/ Colored
Electrochromic				
Low-E Absorptive				
Double, EC Abs, 1LE, air (6ECA-6.3-LE6)	0.52/0.15	0.60/0.17	0.65/0.08	2.40 (0.42)/2.40 (0.42)

TABLE 2
Commercial Building Energy Study
Electrochromic Control Strategies Analyzed

NONE: No control (clear state)

R12 Radiation control #1
- Incident solar radiation = 100 W/m2 : clear state
- Incident solar radiation = 400 W/m2 : colored state
- Linear variation in between
- All windows

R22 Radiation control #2
- Incident solar radiation = 100 W/m2 : clear state
- Incident solar radiation = 600 W/m2 : colored state
- Linear variation in between
- All windows

T12 Temperature control #1
- Indoor air temperatue = 22_C : clear state
- Indoor air temperature = 24_C : colored state
- Linear variation in between
- All windows

T22 Temperature control #2
- Indoor air temperatue = 22_C : clear state
- Indoor air temperature = 26_C : colored state
- Linear variation in between
- All windows

b. Residential Buildings

(1) Highly Insulated

Summary

Residential building analysis in Norway (Ref. 2) consist of a parametric study of high performance glazings at high latitudes (Oslo: 59.9N and Tromsø: 69.7N) with an emphasis on conventional present value economic analysis. A typical Nowegian single-story wood-frame dwelling with a floor area of 105.1 m^2 (1131 ft^2) was chosen as a base case and levels of wall/roof/floor thermal insulation levels and internal gains were varied. Both direct gain windows and sun spaces were analyzed. Results showed that the window solar energy transmittance can be sacrificed in favor of U-factor to obtain higher energy savings. Also, the insulation value of the walls, roof, and floor and the internal heat gains have little effect on the definition of an optimum glazing.

Discussion

Since, window prices vary significantly and are dependent on window size, sales quantity, and manufacturer, the economic analysis was based on average marginal costs compared to a selected base case glazing. Using conventional present value economics, the optimum glazing for a standard Norwegian dwelling was a double pane window with one low-E coating and an argon gas fill. Applying the same present value methodology to analyze the cost effectiveness for an add-on sunspace to the dwelling, it was shown that the optimum glazing was a double pane with one low-E coating when the sunspace temperature was kept at a minimum of 10C-15C (50F-59F). If the temperature was permitted to go as low as 5C (41F), a single glazing with a low-E coating was the most cost-effective.

Table 3 shows the glazings that were analyzed during the course of the study. They vary from a standard double pane clear glazing with a total U-factor of 2.9 W/m^2K (0.51 $Btu/h\text{-}ft^2F$) and center-of-glass solar heat gain coefficient (SHGC) of 0.75 to a quadruple pane superwindow with a U-factor of 0.8 W/m^2K (0.14 $Btu/h\text{-}ft^2F$) and SHGC of .40. In addition, two hypothetical glazings: vacuum and aerogel were also simulated. The vacuum glazing provides better solar transmission than the quadruple glazing while maintaining the same level of conductance; the aerogel provides better conductance than the quadruple glazing while maintaining the same level of solar transmission.

Figure 5 shows the annual heating energy consumption for several of the above glazing types for different residential envelope insulation standards. Windows were distributed on the four facades as follows: North - 3.9 m^2 (42 ft^2); South - 22.2 m^2 (240 ft^2); East - 1.4 m^2 (15 ft^2; and West - 0.5 m^2 (5.4 ft^2). Results show a steadily decreasing heating energy demand as the U-factor of the glazing decreases, even though the amount of beneficial solar heat gain also decreases. For the vacuum window #7, the solar gain increases and there is a corresponding further decrease in required heating. We see that a poorly insulated building with vacuum windows performs about the same as a well insulated building with double pane low-E windows #2. As expected, the differences between the various window types and insulation standards are more significant for the colder and less sunny climate of Tromsø. The overall heating demand is about 20% higher for Tromsø than for Oslo.

The economic analysis was based on the Present Value Method with an energy price of 0.50 Norwegian Krone/kWh (0.075 US Dollar/kWh) a discount rate of 7% and a window lifetime of 25 years. We compared the cost effectiveness of replacing all the standard double pane windows of the residence with more advanced window types. Results are presented in Table 4. Cost effectiveness is expressed as the difference between the present value of the energy savings and the investment cost associated with a particular glazing. A positive value signifies a cost effective investment.

In general, one can see that the advanced windows are more cost effective in Tromsø than in Oslo. This is due to its colder climate and the longer heating season. For all cases, the double pane window with one low-E coating and argon gas fill (window #3) is the most cost effective. It is important to note that the double pane glazings with low-E have been on the market for several years and have become a standard, mass-produced product. The triple- and quadruple-pane glazings are sold in much smaller quantities and are priced higher. The vacuum and aerogel windows are still in the development phase and so there are no market prices as yet.

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TABLE 3
Glazing Solat/Optical/Thermal Properties

Glazing	SHGC(Tset)	SC	Tvis	U-Factor (COG/Total) W/m^2-K (Btu/h-ft^{2}F)
1. Double, air (4-12-4)	0.75	0.86		2.9 (0.51) / 2.7 (0.48)
2. Double, 1 LE, air (4-12-LE4)	0.61	0.70		1.8 (0.32) / 2.0 (0.35)
3. Double, 1 LE, argon (4-12A-LE4)	0.61	0.70		1.5 (0.26) / 1.7 (0.30)
4. Triple, 1 LE, air, argon (4-12-4-12A-LE4)	0.54	0.62		1.2 (0.21) / 1.5 (0.26)
5. Triple, 2 LE, air, argon (4LE-12A-4-12A-LE4)	0.45	0.52		0.9 (0.15) / 1.3 (0.23)
6. Quadruple, 3 LE, argon (4LE-18-4LE-16A-4-16A-LE4)	0.40	0.46		0.5 (0.09) / 0.8 (0.14)
7. Double, 2LE, vacuum (4LE-12V-LE4)	0.52	0.60		0.8 (0.14) /0.8 (0.14)
8. Double, aerogel (4-20-4)	0.64	0.74		0.5 (0.09) /0.7 (0.12)

TABLE 4
NORWAY Cost Effectiveness of Glazing Types

OSLO NOK/m2 (US$/m2, US$/ft2)

GLAZING	Present Value Savings	Investment Cost	Cost Effectiveness
2	460 (68, 6.32)	160 (24, 2.23)	300 (45, 4.18)
3	690 (103, 9.57)	230 (34, 3.16)	**460 (69, 6.41)**
4	740 (110, 10.22)	500 (75, 6.97)	240 (36, 3.34)
5	840 (125, 11.61)	650 (97, 9.01)	190 (28, 2.60)
6	1190 (178, 16.54)	1850 (276, 25.64)	-660 (-98, -9.10)
7	1300 (194, 18.02)	---	---
8	1420 (212, 19.69)	---	---

TROMSØ NOK/m2 (US$/m2, US$/ft2)

GLAZING	Present Value Savings	Investment Cost	Cost Effectiveness
2	560 (84, 7.80)	160 (24, 2.23)	400 (60, 5.57)
3	850 (127, 11.79)	230 (34, 3.16)	**620 (93, 8.64)**
4	910 (136, 12.63)	500 (75, 6.97)	410 (61, 5.67)
5	1020 (152, 14.12)	650 (97, 9.01)	370 (55, 5.11)
6	1470 (219, 20.35)	1850 (276, 25.64)	-380 (-57, -5.30)
7	1620 (242, 22.48)	---	---
8	1770 (264, 24.53)	---	---

SPAIN

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SIMULATION RESULTS: Spain

The present report summarizes work concerning the influence of coated glazings on the energy saving potential in a commercial office building and a residential apartment building. In the commercial building study, we focused on the performance of several types of solar control glazings varying from a conventional double pane tinted window to a high performance spectrally selective window. For the residential apartment analysis, the performance of more conventional low-e units was evaluated. The study was completed for three locations in Spain: Madrid, Seville, and Cadiz. The TRANE building energy simulation program was used as the simulation tool.

a. Commercial Buildings

(1) Solar Control Glazings

<u>Summary</u>

In cooling dominated cities like Madrid, Seville, and Cadiz, specific weather data did not affect cooling energy consumption in any of the glazed office buildings simulated, although heating energy consumption did. The design cooling capacity is greater than the desing heating capacity for each glazing analyzed. For coated glazings, the use of sputter reflective coatings on tinted glass combined with low-emissivity coatings on clear glass produced the largest savings in cooling energy in each city; and the use of double glazing with one low-emissivity coating on a tinted glass second surface, the least. The use of spectrally selective low-emissivity coatings on tinted glass combined with low-emissivity coatings on clear glass show considerable building energy savings. Furthemore, this glazing system had the most efficient glazing luminosity than the other glazings and thus light is not sacrificed for solar control .

<u>Discussion</u>

A building which was under construction in Madrid was selected the base case office building. It represents a typical high-standard curtain-wall office building with a floor area of 7813 m2. There are eight floors, with the last three stories being smaller on the longitudinal axis. An unconditioned parking area occuping three underground floors is also provided. The long axis faces south and t he office building is not shaded by any neighboring buildings. The office building envelope is a 3952 m2 external curtain-wall (40% of the building envelope is glazed); the roof has a total area of about 1060 m2 (300mm light-weight concrete, U-value of 0.45 W/m2C); the ceiling consists of 400 mm light-weight concrete; the glazed envelope has 6/12.7/6 mm double glazing units.

The total lighting density for the offices is 21 W/m2, the lighting load for the parking area is 15 kW and the miscellaneous equipment load is put at 5 W/m2 . The lighting and the equipment loads are assumed to be steady state. The base case building has a maximun occupancy of 780 people, which occurs during peak periods every week; 10 m2/ person are considered. The HVAC system type is variable temperature constant volume. The airflow supply is 0.007 m3/s person. The HVAC plant and equipment are as follows: (a) cooling, three 3x600kW capacity reciprocating parallel-sequencing chiller plus a cooling tower; (b) heating, one 600kW capacity gas boiler and

8kW peak demand for domestic hot water. The energy purchases are electricity, gas and hot water.

Coated glazing is an envelope technology that reduces solar gains, increasing comfort and reducing cooling loads in hot climates. For this study, the glazing types selected included three air-filled double glass units (DGU) with such second surface coatings as reflective, low-emissivity or spectrally selective outer tinted glass, the DGU having a clear glass inner pane; and three additional DGU's incorporating a low emissivity coating on an inner clear glass third surface so that solar gain control combines with thermal insulation. As uncoated glazed systems, both an air-filled double-glazed system consisting of a tinted glass outer pane and a clear glass inner pane, and a double clear glazed unit to be used as a reference were selected. The solar optical and thermal properties of the glazing systems selected, as shown in Table 1, were calculated using the Window 4.1 program.

The reduction in the design cooling capacity, which is based on the building peak cooling load, shows a dependency on the glazing system solar heat gain as can be seen in Figures 1 and 2. Due to its lower solar heat gain coefficient, the reflective low-e (glazing #3) combination of solar control with thermal insulation significantly reduces the building cooling plant size by about 24% in each city. On the other hand, all the coated glazings, with the exception of the tinted low-e glazing (#4), resulted in similar reductions in total electric power demand (Figures 3 and 4). Figures 5 and 6 show that design heating capacity decreases as city insolation increases, and therefore Cadiz has the greatest reduction in heating plant size for each glazing type examined Glazing #3 through # 7 show a 12% to 15 % reduction in heating plant size in each city when compared to the reference double pane clear glazing system.

As shown in Figures 7 and 8, total electric power consumption decreases as a function of the glazing system solar heat gain for all glazings. For example, glazing #2 and # 7, which both have a shading coefficient of SC= 0.30 but different U-values of 2.96 and 1.70 W/m^2 C respectively, produced similar electric power savings. Glazing #3 has the largest reduction of 23.4%.
This glazing reduced the cooling energy consumed approximately 344 MWh/year in Madrid, 327 MWh/year in Seville, and 281 MWh/year in Cadiz compared to the reference clear double glazing (Figures 9 and 10). Glazing #2, because it reflects solar heat, produced the greatest increases of 151 GJ in Madrid, 67 GJ in Seville, and 34 GJ in Cadiz, in gas consumption for heating and domestic hot water compared to the reference double clear glazing (Figure 11). The annual building energy consumption in MJ/m^2 for each glazing simulated is roughly the same for each city. The best energy savings of 21.8% in Madrid, 21.5% in Seville, and 18.9% in Cadiz were achieved with glazing #3 (Figures 12 and 13).

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TABLE 1
Commercial Building Energy Study
Glazing Solar/Optical/Thermal Properties

	GLAZING	SHGC(Tset)	SC	Tvis	U-Factor - COG W/m^2-K (Btu/h-ft^2F)
Ref	Double, Air (6-12.7-6)	0.75	0.87	0.80	3.12 (0.55)
1.	Double, Tint, Air (6T-12.7-6)	0.48	0.56	0.66	3.27 (0.58)
2.	Double, Refl, Air (6RE-12.7-6)	0.26	0.30	0.21	2.96 (0.52)
3.	Double, Refl, 1LE, Air (6RE-12.7-LE6)	0.20	0.23	0.18	1.99 (0.35)
4.	Double, 1LE, Air (6LE-12.7-6)	0.41	0.48	0.52	1.93 (0.34)
5.	Double, 2LE, Air (LE-12.7-LE6	0.37	0.40	0.47	1.79 (0.32)
6.	Double, 1SS, Air (6SS-12.7-6)	0.29	0.34	0.41	1.71 (0.30)
7.	Double, 1SS, 2LE, Air (6SS-12.7-LE6)	0.26	0.30	0.37	1.70 (0.30)

b. Residential Apartment Buildings

(1) Conventional Insulated Glazings

Summary
In Spain, 86.5% of the residential apartment buildings have hot water, 39% central heating, and 1.1% air conditioning. Some buildings have individual window or split-type cooling systems and 7.8% have elevators. This study investigated the energy savings in the cooling-dominated cities of Madrid, Seville and Cadiz of several different types of insulating glazings in an existing high-standard apartment building. The TRANE building energy simulation program was used

All the glazings resulted in a similar behavior pattern in the three cities. The use of double low-e glazing reduced the cooling load 40% and the heating load 20%. The results show that for highly-glazed air conditioned apartment buildings in a climate such as Madrid, the replacement of single glazing by uncoated double glazing produced the best cost-benefit relationship with an annual building energy saving of 16% . Considering an installed double glazing cost of 4408 pts/m^2, the total price of replacing the 4,986 m^2 is about 22.0 Mpts ($175,000) assuming amortization over 5 years. For an installed double pane low-e with clear glazing cost of 9708 pts/m^2, the total price of replacement is about 48.5 Mpts ($385,000); and for an installed double pane consisting of two low-e glazings with a cost of 11708 pts/m^2, the total price of replacement is about 58.4 Mpts ($463,000). Both double low-e glazings exceed the standard amortization.

Discussion
The building simulated is an existing 25-floor apartment building located in Madrid. The first three floors are used by offices and the ground floor contains the reception area and a bar-restaurant. The remaining floors are apartments. The building, which was built in the late 1970s , has a volume of 44 x 22.5 x 77 = 76230 m^3 . The main facade is east-west oriented and is partially shaded by the sourrounding buildings. All the apartments have large window terraces with 4m wide overhangs. The building has two floors of unconditioned underground parking below the ground floor. The corridor, aisles, warehouses, elevators, and stairways are also unconditioned. The total conditioned building area is approximately 14000 m^2, which corresponds to 55% of the total.

We compared four window types varying from single pane clear to a double pane unit of two low-e glazings (Table 2). The cooling loads shown on Figure 1 have a similar pattern for the three cities for each glazed building. The use of double glazed units with two low-e coatings had the greatest decrease in cooling loads. For heating loads, Figure 2, the use of double clear glazing reduced the load by 27% to 30% over single clear glazing in all the cities. The use of the low-e glazing systems, due to their lower U-value, reduced the total heating load of the single-glazed building 40% to 43%. Since the heating load is a function of the design winter dry bulb temperature, the heating loads are lower than cooling loads for each glazed building simulated in the three cities, except for the single glazed building in Madrid.

The energy consumption provides information on the seasonal behaviour and part-load performance of the building systems. Figure 3 shows the yearly electrical power consumption in

MWh. It may be observed that the uncoated and coated double-glazed building led to a 4% to 20% decrease in total electric power consumption in each city when compared to the building using single clear glazing. The electricity consumption for the cooling systems with electric compressors represented about 35% of the total electricity consumption for this building.

As shown in Figure 4, the cooling energy consumption for each building is a function of the city insolation. The double pane with two low-e glazings had the best savings in annual cooling energy varying from 18% to 25%. As expected, annual oil consumption shown on Figure 5 is related to heating degree-day values. The best savings was observed with the use of the double pane low-e clear glazing, although all uncoated and coated double glazings had significant oil consumption savings in comparison to the single-glazed building.

The annual building energy consumption in terms of MJ/m^2 per year is an indicator of the whole building energy performance. Figure 6 shows that the annual building energy saving increases with city insolation, the improvement in U-value disminishes thermal loss, but the lower shading coefficient negatively affects solar gains, so the difference among glazings is less marked in cities with higher insolation. Both the double pane windows using low-e glazings had similar energy efficiency in spite of the improved U-value and solar heat gain coefficient of the unit utilizing two low-e glazings. The use of uncoated double glazing reduces annual building energy consumption by about 10% to 16% and the double pane low-e clear by about 23% to 17%. The double pane window with two low-e glazings does not improve building energy efficiency compared to results using just one low-e glazing.

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TABLE 2
Residential Building Energy Study
Glazing Solar/Optical/Thermal Properties

GLAZING	SHGC(Tset)	SC	Tvis	U-Factor - COG W/m^2-K (Btu/h-ft^2F)

Single (4)	0.87	1.01	0.90	5.70 (1.00)
Double, Air (4-12.7-4)	0.78	0.90	0.82	3.11 (0.55)
Double, 1LE, Air (6LE-12.7-6)	0.60	0.70	0.72	1.85 (0.33)
Double, 2LE, Air (6LE-12.7-LE6)	0.50	0.58	0.65	1.71 (0.30)

SWITZERLAND

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SIMULATION RESULTS: Switzerland

Parametric studies highly insulating glazings in a commercial office building and highly insulating glazings and transparent insulation material (TIM) on opaque walls in a multifamily house have been investigated. Questions of interest were the energy consumption during the heating period from October 1st to April 30th due to the different glazings and due to different orientations of the building, the relationship between solar gain and thermal transmission losses, the influence of the various Swiss climates, the energy saving potential of TIM and also questions related to comfort such as the temperature of the inner surfaces and air temperatures. The simulations were performed using the program HELIOS, which was developed at EMPA. HELIOS is based on a single zone model and calculates in hourly steps the heat balance for each part of the building.

a. Commercial Buildings

(1) Superinsulated

<u>Discussion</u>
The office building is well insulated (flat roof and walls mean U-values < 0.33 W/m2K). There are 5 floors of 493 m2 each made of concrete so there is a lot of thermal mass. The inner partitions are made of thin plaster double plates. The ratio of window area to floor area is 30% with 60% of the window area being glazing and 40% framing. There is a main facade that is twice as long as the other facade. The ratio of window to wall area is 55% to 45% on all facades. The main facade is first oriented south and then to the east. The offices are arranged around a centre room with infrastructure such as cafeterias, etc. This centre room is assumed to be well conditioned at a temperature of 18 C. There is only thermal transmission to this room (no air change).

The mean air change rate during office hours is 0.80 h-1 (for hygienic reasons there should be an air change rate of at least 0.62 h-1). During unoccupied hours, the air change rate is 0.2 h-1. The mean internal loads are 19'981 W. Heating occurs when the room air temperature falls below 20C. Heating is switched off from 21'00 to 05'00. There is sun protection with venetian blinds with solar irradiation in the room decreased by a factor of 0.2 if global radiation in the window plane is higher than 350W/m2.

Four different climates were investigated: Davos, an alpine climate with much sunlight; Zurich, a cold climate and little sun; Geneva, quite a warm climate but not much sun; and Magadino which can be quite a warm climate with much sunligth.

The four glazings presented on Table 1 were simulated. They vary from double pane with clear glazing and air gas fill with a total U-factor of 2.70 W/m^{2}K (0.48 Btu/h-ft^{2}F) and center-of-glass solar heat gain coefficient of 0.78 to a triple pane using clear and low-E glazing layers and krypton gas fill with a U-factor of 0.69 W/m^{2}k (0.12 Btu/h-ft^{2}F) and solar heat gain coefficient of 0.40. Window area varied from 0% to 30% of the floor area.

<u>Results</u>

Figure 1 shows the heat flux balances for the building for the different glazing types. The losses due to the ventilation are only dependent on the mean room air temperature and so within one climate they are nearly the same (+/- 2%) for all cases. They range from approximately 25% (window 0, double glazing with air filling and no coating) to 45% (window 3) of the losses. The transmission losses come to approximately 20 to 40%. Losses through the windows make approximately 60% total losses for the worst case (window 0). These losses can be reduced by 65%, using the window type 3. We should mention that switching from type 0 to type 1 causes a reduction in losses of 32%, which is half of the reduction potential. The solar gains influence the total performance. As in Figure 1, window type 0 has the biggest solar heat gains. There is a clear difference between type 1 and type 2 because of the 32% lower SHGC. Because of the sun protection device, the importance of the solar heat gain is not very large.

The effective heating demand shown on Figure 2 is determined by the energy balance of gains and losses. Window type 0 has the highest energy demands in all climates. This is because the losses due to the very high U-value cannot be compensated for by the solar gains. Improving the window to type 1 reduces the demands significantly by about 30%. Further improvement using types 2 or 3 do not make such a big difference but still can result in a further reduction of about 10% to 15% each. The total possible improvement is about 45% to 50% of energy. Because the glazing area is uniformly distributed on all facades, the heating demand is nearly the same for east and for south orientation. It is a little bit lower for east orientation because sun protection is less active and solar heat gains are higher.

During office hours, it is difficult to keep the temperature at 20C because of the high air change rates with outdoor air. The temperature swings between 19.5 and 20 degrees. When heating is switched off during the night between 22'00 and 05'00, the temperature can drop significantly below 20 C. In the cold climate of Davos, the temperature drops below 15C and for the warm climate of Magadino, there is a minimum of about 16C. During this seven hour period, temperature can fall about 5 degrees which causes no problem with comfort because the building is heated up very quickly before it is used.

In designing the optimal window, one has to keep in mind that the optimal performance of a window depends on the climate and also the specific use of the window. In most offices, sun protection is absolutely necessary, so the U-value is of importance in the heating-dominated climates of Switzerland.

Table 1
Commercial Building Glazing Properties

GLAZING	SHGC	SC	Tvis	U-Factor, COG/Total W/m^2-K (Btu/h-ft^{2}F)
0. Double, air (4-12-4)	0.78	0.90	0.74	2.88 (0.51)/2.70 (0.48)

1. Double, 1LE, argon (4-12A-LE4)	0.65	0.75	0.52	1.32 (0.23)/1.50 (0.26)
2. Triple, 2LE, argon (4-12A-LE4-12A-LE4)	0.44	0.51	0.32	0.84 (0.15)/0.99 (0.17)
3. Triple, 2LE, krypton (4-12K-LE4-12K-LE4)	0.40	0.46	0.30	0.47 (0.08)/0.69 (0.12)

b. Multifamily House

(1) Superinsulated and TIM

Discussion

The multifamily house is well insulated (flat roof and walls with mean of U-values < 0.23 W/m2K) . There are 4 floors of 361 m2 each made of concrete with inner partitions made of brick resulting in a high level of thermal mass. For the TIM study, we compared brick walls with U-values of 1.05 W/m and 0.29 w/m2K to a brick wall with 12 cm of TIM with a total U-value of 0.49 W/m2K. The ratio of window area to floor area is 20%. 80% of the window area is glazing and 20% is frame. There is a main facade containing 57% of the window area. Its orientation was varied to face south, east, and west. The TIM is fitted on the main facade. The mean air change rate is 0.3 h-1 (hygienic reasons require an air change rate of at least 0.24 h-1). The mean internal loads are 5588 W and correspond to the mean values for a typical Swiss household. Heating starts when the room air temperature falls below 20 C. Heating is switched off from 23'00 to 05'00.

Four different climates were investigated: Davos, an alpine climate with much sunlight; Zurich, a cold climate and little sun; Geneva, quite a warm climate but not much sun; and Magadino which can be quite a warm climate with much sunligth.

The four glazings presented on Table 2 were simulated. They vary from double pane with clear glazing and air gas fill with a total U-factor of 2.70 W/m^2K (0.48 $Btu/h\text{-}ft^2F$) and center-of-glass solar heat gain coefficient of 0.78 to a triple pane using clear and low-E glazing layers and krypton gas fill with a U-factor of 0.69 W/m^2k (0.12 $Btu/h\text{-}ft^2F$) and solar heat gain coefficient of 0.40. Window area varied from 0% to 30% of the floor area. For the TIM cases, window type 1 was used. The properties of TIM include a thermal conductance of 0.73 W/m2K and SHGCs of direct equal to 0.83 and diffuse 0.56.

Highly Insulated Glazings

Figure 3 shows the heat flux balances for a south orientation. The losses due to the ventilation are only dependent on the mean room air temperature and so for any one climate they are nearly the same (+/- 10%) for all windows analyzed. They make approximately 1/3 of the losses. The transmission losses come to approximately 1/6 of all. Losses through the windows make approximately half of total losses for the worst case using double glazing with air filling and no coating. These losses can be reduced by 75%, using window type 3. Here we have to mention, that the step from type 0 to type 1 already causes a reduction in losses of 36%, which is half of the reduction potential. The solar gains are important in determining total performance. As seen in Figure 3, window type 0 has the largest solar heat gains. There is a clear difference between window types 1 and 2 because of the 32% lower SHGC of type 2. The advanced windows have not only a low U-value reducing the thermal losses, but also a lower SHGC which reduces the solar gain.

Figure 4 shows energy consumption for south and east orientations. The effective heating demand is determined by the energy balance of gains and losses. Window type 0 has the highest energy demands in all climates. This is because the losses due to the very high U-value can't be compensated by the solar gains. Improving the window to type 1 reduces the demands significantly by about 1/3. Further improvement to types 2 or 3 doesn't make much difference because the smaller losses are compensated by also smaller solar gains. This is especially obvious in the sunny climates of Davos and Magadino, where the "better" windows types 2 and 3 show even higher demands than type 1. Therefore, the energy performance even in the not very sunny climate of Zurich is strongly dependent on the solar heat gains and therefore on the SHGC. One sees also, that changing the orientation makes a large difference in energy demands because of much more solar gains when turning the main facade with many windows to south.

When heating is on, there is enough heating power to keep the room air temperature at 20C. Only when heating is switched off during the night between 23'00 and 05'00 can the temperature fall significantly below 20 C. With an east orientation and in the cold climate of Davos, the temperature doesn't fall below 17.1C; for the warm climate of Magadino, there is a minimum of 18C. Therefore, during this six hour period, the temperature only falls about 3 degrees which produces no problem with comfort since the building is heated very quickly. The maximum temperature reached is 28.3C in Magadino for window type 1. Concerning the low outer air temperatures during the heating period, cooling can be achieved by raising the amount of air ventilation. Nevertheless, in summer time, this window may cause problems if there is no sun protection.

Figure 5 shows inside surface temperatures in Davos. For all types, the distribution is quite smooth and very similar. For types 1 to 3, there is an shift of about 6C to 8C compared to the distribution of type 0. Type 0 is at a temperature of less than 18C more than 85% of the time which is 2C below the heating temperature. Because of the cold air drop near the glazing, this difference is critical for comfort. Therefore, type 0 definitely requires support from a radiator. Type 1 is below the comfort limit about 40% of time, and therefore also needs radiator support. The high tech windows are at temperatures below 18 C less than 4% of time (only at night time), and so they can be used without support of radiators, and open new possibilities for design, i.e., floor heating etc. Because of absorption, there can quite often be high temperatures at the inner surface, specially with window type 1.

In designing the optimal window one has to keep in mind that the optimal performance of a window depends on the climate and also on the specific use and orientation of the window. There has to be found an optimum between reducing losses (low U-value) and rising solar gains (high SHGC). Depending on the general building properties (thermal mass, ratio of window to floor area) and solar supply, there is a meaningful maximum for the SHGC, because there is a maximum of gain that can be used without overheating. Therefore the optimum is specific for the different climates and building types. In this investigation ,the energy saved by a reduction of U-value of 1 W/m2K corresponds approximately to the solar gains lost by a reduction of SHGC of 0.42.

<u>Transparent Insulation Material (TIM)</u>

Figure 6 shows the heat flux balances for a south orientation in Davos. In December the biggest losses arise corresponding to the low temperature and the short sunshine period during the day. If opaque insulation is improved, the losses can be reduced significantly, but at best to zero. On the other hand, using TIM can produce gains instead of losses. In the sunny climate of Davos, there are substantial gains on south facade during the winter months. On east or west facades there are high gains only in the transition months.

Figure 7 shows energy consumption for south, east , and west orientations. The heating demands are quite low because of high overall insulation levels even with the uninsulated brick wall. Adding opaque insulation reduces the heating demand significantly in all climates. If transparent insulation is fitted on the south wall, the energy demands decline by about 50 MJ/m2 in Davos, 25 MJ/m2 in Zurich and 30 MJ/m2 in Magadino compared to opaque insulation. Thus TIM help in achieving zero building heating demand.

The mean inner surface temperatures of the wall reach about 17C to 18C with only a brick wall. Adding the insulation raises the mean temperature to about 19.7C to 20.1C, whichh is very near to the mean room air temperature. With the TIM, the temperatures rise to 23C to 26C. Inner surface temperatures are much higher with TIM, which is what most people feel as very comfortable.

Table 2
Multifamily Building Glazing Properties

GLAZING	SHGC	SC	Tvis	U-Factor, COG/Total W/m^2-K (Btu/h-ft^{2}F)
0. Double, air (4-12-4)	0.78	0.90	0.74	2.88 (0.51)/2.70 (0.48)
1. Double, 1LE, argon (4-12A-LE4)	0.65	0.75	0.52	1.32 (0.23)/1.50 (0.26)
2. Triple, 2LE, argon (4-12A-LE4-12A-LE4)	0.44	0.51	0.32	0.84 (0.15)/0.99 (0.17)
3. Triple, 2LE, krypton (4-12K-LE4-12K-LE4)	0.40	0.46	0.30	0.47 (0.08)/0.69 (0.12)

Figure 3: Heat flux balance of walls for south orientation of building
Gains: QS = solar gains, QH = heating demand, Qint = internal loads
Losses: QT = thermal transmission, QL = Losses due to air ventilation

Figure 4: Energy needs per floor area for different window types and orientations

Figure 5: Frequency distribution of inner surface temperatures of glazings for Davos, south orientation

Figure 6: Heat flux through walls of main facade when oriented to south in Davos climate. Positive flux is flowing into the building.

Figure 7: Energy consumption per floor area for different constructions and orientations with TIM

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SIMULATION RESULTS: United States

Work in the United States has focused on the performance of electrochromic and angular selective glazings in commercial (Refs. 1, 2, 3, 4) and electrochromic and evacuated glazings in residential buildings (Refs. 5, 6). Each analysis simulated the performance in either cooling or heating dominated locations. In the case of the electrochromic glazings, we focused on the particular properties of the window, and also investigated electrochromic state-switching control strategies. Basic solar/optical performance was emphasized in evaluating the angular selective glazing; and for the evaculated glazings, we introduced several advanced superwindows into the analysis as alternatives to the evacuated glazings. Results obtained for all the advanced glazings were compared to more conventional glazings using the DOE-2.1 E simulation program to calculate annual heating and cooling energy use and peak electric demand.

a. Commercial Buildings

(1) Electrochromics

Summary: Cooling and Lighting Energy Performance

This study (Ref. 1) investigated the energy performance of electrochromic windows in a prototypical commercial office building module under a variety of state-switching control strategies. We used the DOE-2.1E energy simulation program to analyze the annual cooling, lighting, and total electricity use and peak demand as a function of glazing type, size, and electrochromic control strategy. The module was located in the cooling-dominated location of Blythe, California. Control strategies analyzed were based on daylight illuminance, incident total solar radiation, and space cooling load. Our results show that when a daylighting strategy is used to reduce electric lighting requirements, control algorithms based on daylight illuminance results in the best overall annual energy performance. If daylighting is not a design option, controls based on space cooling load yield the best performance through solar heat gain reduction. The performance of incident total solar radiation control strategies varies as a function of the switching setpoints; for small to moderate window sizes which result in small to moderate solar gains, a large setpoint-range was best since it provides increased illuminance for daylighting without much cooling penalty; for larger window sizes, which provide adequate daylight, a smaller setpoint-range was best to reduce unwanted solar heat gains and the consequential increased cooling requirement. Of particular importance is the fact that reduction in peak electric demand was found to be independent of the type of control strategy used for electrochromic switching. This is because the electrochromics are generally in their most colored state under peak conditions, and the mechanism used for achieving such a state is not important.

Discussion

The performance of electrochromic windows was analyzed by completing hour-by-hour DOE-2 building energy simulations to evaluate the annual energy consumption and peak demand of a prototypical commercial office building module. The module consisted of a 30.5m (100ft) square core zone, surrounded by four identical perimeter zones, each 30.5m by 4.6m (100ft by 15ft) facing four cardinal directions. Each perimeter zone was divided into ten office spaces of equal size with a floor-to-floor height of 3.7m (12ft) and floor-to-ceiling heigh of 2.6m (8.5ft). Each zone was assumed to have its own constant-volume variable-temperature HVAC system. The window-to-wall area ratio (window area expressed as a fraction of the floor-to-floor facade) was varied from 0.0 to 0.6. This represents 0.0 to 0.85 of the floor-to-ceiling wall area. Lighting power density was 16.1 W/m^2 (1.5 W/ft^2).

We compared the performance of real clear and low-E absorptive and reflective electrochromics to an idealized highly reflective electrochromic and to several conventional glazings in Blythe, California, a cooling dominated location. The electrochromics are IG units with an inner pane of either clear or low-E glazing (coating on the gap surface) and an outer pane with the electrochromic layer on the gap surface. The solar/optical/thermal properties of the window prototypes are shown in Table 1.

For the absorbing electrochromic, the near-infrared absorptance increases in the colored state; for the reflecting electrochromic, the near-infrared reflectance increases in the colored state. The idealized electrochromic has an electrochromic coating on the inside surface of the outer pane and a relective low-E glazing inner pane. It switches from transmitting to reflecting in the visible portion of the solar spectrum, while maintaining a minimum transmittance and a high reflectance in the near-infrared portion of the spectrum. The solar/optical properties of these electrochromic windows were varied using control strategies based on daylight illuminance, incident solar radiation, or space cooling load.

The objective in cooling dominated locations is to reduce electricity use due to cooling by reducing the solar gain and the electricity use due to lighting by increasing the use of natural light. Figure 1 shows the annual cooling and lighting electricity use components in Blythe, California for west facing idealized and real clear and low-E electrochromic windows as a function of window-to-wall ratio. Workplane illuminance was used to control the electrochromic system properties.

The importance of solar gain control is apparent through the large variation in cooling electricity use. The idealized device has a higher solar transmittance than the real devices in the bleached state, but a significantly lower solar transmittance than the real devices in the colored state. Since the electrochromics mostly operate close to the colored state when cooling is required, this results in lower cooling loads for the idealized device. There is a difference of approximately 22-32 kWh/m^2 (2-3 kWh/ft^2) in cooling electricity between the real and idealized devices at the largest window-to-wall area ratio. This represents 24%-35% of the total (cooling+fan+lighting) electricity use one might expect from a west-facing perimeter zone without windows; i.e. 91 kWh/m^2 (8.5 kWh/ft^2).

Lighting electricity use tends to be the same for all electrochromic devices when using daylight control. Daylight saturation (when the electric lighting is reduced to its minimum) occurs at window-to-wall ratios between 0.2 and 0.3 with a lighting reduction of close to 75% or 32 kWh/m^2 (3 kWh/ft^2) at saturation. The sum of the cooling and lighting electricity is also shown on Figure 1. We see that for window-to-wall ratios less than 0.5, the real electrochromic devices result in less electricity use than perimeter zones that have no windows; i.e. a window-to-wall ratio of zero. The electricity use of the ideal electrochromic never exceeds that of a windowless wall, even for an all glass facade.

Figure 2 gives an indication of electrochromic performance when compared to conventional glazings. The tinted unit has the largest cooling requirement, followed by the low-E glazing, reflective glazing, and idealized electrochromic. For the largest window-to-wall area ratio in a west-facing orientation, there is a difference of 86 kWh/m^2 (8 kWh/ft^2) between the idealized electrochromic and the tinted glazing. This reduces to about 22 kWh/m^2 (2 kWh/ft^2) for the reflective static glazing. Lighting performance for the electrochromics is slightly better than the performance of conventional tinted or low-E windows. The relative peak electricity demand for each of the glazings is very similar to the relative summed annual electricity use performance.

Figure 3 presents the cooling and lighting electricity use for the various control strategies. For all window sizes, we see that daylight control provides the best overall performance, implying that modulation of daylighting results in good solar control modulation as well.. At window-to-wall area ratios less than about 0.35, total electricty performance is more a function of lighting electricity decrease than cooling electricity increase. The use of space cooling load as a control strategy results in the smallest cooling electricity, but also the smallest lighting electricity use reduction due to daylighting. As a result, use of space cooling load results in the largest summed electricity use for all glazings modeled. Cooling load control, however, can be a preferable strategy for those building configurations that do not incorporate daylighting as an energy saving design option.

Summary: Heating Energy Performance

This study (Ref. 2) investigated the energy performance of electrochromic windows in heating-dominated geographic locations using different state-switching control strategies. We used the DOE-2.1E energy simulation program to analyze a prototypical commercial office building module located in Madison, Wisconsin. Control strategies analyzed were based on daylight illuminance, incident solar radiation, and space cooling load. Our results show that overall energy performance is best if the electrochromic is left in its clear or bleached state during the heating season, but controlled during the cooling season using daylight illuminance as a control strategy. However, having the electrochromic remain in its bleached state during the winter season may result in glare and visual comfort problems for occupants much in the same way as conventional glazings.

Discussion

The energy performance evaluation of electrochromic glazings in commercial buildings has focused primarily on their ability to reduce cooling load by minimizing solar heat gains and reduce electric lighting by the use of natural light or daylighting. To date, not much work has been completed analyzing the performance of electrochromics in geographic locations which are dominated by large heating loads. We present in Ref. 2 an analysis of electrochromic performance in the heating-dominated location of Madison, Wisconsin. Madison is characterized by having cold winters and hot and humid summers.

We compared the performance of six electrochromic windows as shown on Table 2. Two of the electrochromic materials have low reflectance levels typical of most devices; these are designated as types (80/20) and (80/10) representing the minimum and maximum visible transmittance levels of the electrochromic layer. These devices function primarily by changing absorptance and are intended to represent readily achievable performance. Two additional materials have reflectance levels that increase significantly in the colored state; these are designated (G) and (GX) and represent devices that may be available sometime in the future. Each of the two low reflective glazings, (80/20) and (80/10), was combined with either of two idealized types of low-E glazings. The first, which is designated (E) is a clear glass with a low emittance; the second, designated (S), is a spectrally selective glazing with the same emittance as the (E) glazing, but a greatly enhanced reflectance in the solar infrared.

The heating performance of electrochromic devices is the same as that of a conventional glazing which has the same the same U-factor and solar heat gain coefficient. However, this is only true for an electrochromic control strategy which does not result in state-switching during the winter months; in our example, which we discuss below, such a situation occurs with space cooling load control. Electrochromic devices that switch in winter and thus result in a smaller amount of beneficial solar heat gain can be expected to result in larger heating requirements than conventional glazings. The magnitude would be similar to what is seen here for the different control strategies compared to space cooling control.

We present heating energy requirements for a south-facing window on Figures 4 which shows results as a function of electrochromic glazing type for each of the control strategies. We see that the E-type low-E clear glazings have about 10% lower heating energy values than the S-type spectrally selective glazing for each of the window-to-wall area ratios and control strategies. This is a direct result of the higher solar heat gains associated with the E-type glazings. The GE glazing consistantly performs better than the GXE glazing, from 10-20%, for all control strategies except for space cooling load control, in which case the performance is about equal. As stated previously, space cooling control is not implemented in winter and so the heating performance of the GE and GXE should be the same because their bleached properties are the same.

References

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TABLE 1
Commercial Building Energy Study
Electrochromic Solar/Optical/Thermal Properties

	SHGC(Tset) Bleached/ Colored	SC Bleached/ Colored	Tvis Bleached/ Colored	U-Factor - COG W/m^2-K (Btu/h-ft^{2}F) Bleached/ Colored
Electrochromic				
Clear Absorptive Double, EC Abs, air (6ECA-6.3-6)	0.73/0.18	0.85/0.21	0.76/0.14	2.43 (0.43)/2.43 (0.43)
Clear Reflective Double, EC Refl, air (6ECR-6.3-6)	0.63/0.17	0.73/0.20	0.73/0.14	2.43 (0.43)/2.43 (0.43)
Low-E Absorptive Double, EC Abs, 1LE, air (6ECA-6.3-LE6)	0.44/0.16	0.51/0.18	0.66/0.10	2.33 (0.41)/2.33 (0.41)
Low-E Reflective Double, EC Refl, 1LE, air (6ECR-6.3-LE6)	0.46/0.16	0.53/0.18	0.64/0.12	2.33 (0.41)/2.33 (0.41)
Idealized	0.58/0.05	0.67/0.06	0.65/0.00	2.38 (0.42)/2.40 (0.42)
Conventional				
Double, Tint, air (6T-12.7-6)	0.47	0.54	0.38	2.74 (0.48)
Double, Refl, air (6RE-12.7-6)	0.17	0.20	0.13	2.35 (0.41)
Double, Tint, 1LE, air (6LE-12.7-6)	0.31	0.35	0.41	2.41 (0.42)

TABLE 2
Commercial Building Energy Study
Electrochromic Solar/Optical/Thermal Properties

	SHGC(Tset) Bleached/ Colored	SC Bleached/ Colored	Tvis Bleached/ Colored	U-Factor - COG W/m^2-K (Btu/h-ft^2F) Bleached/ Colored
Electrochromic				
80/20E Double, EC, 1LE, air (6EC-6.3-LE6)	0.64/0.23	0.74/0.27	0.65/0.16	2.37 (0.42)/2.37 (0.42)
80/20S Double, EC, 1SS, air (6EC-6.3-SS6)	0.52/0.20	0.60/0.24	0.65/0.16	2.37 (0.42)/2.37 (0.42)
80/10E Double, EC, 1LE, air (6EC-6.3-LE6)	0.64/0.16	0.74/0.20	0.65/0.08	2.37 (0.42)/2.37 (0.42)
80/10S Double, EC, 1SS, air (6EC-6.3-SS6)	0.52/0.15	0.60/0.17	0.65/0.08	2.37 (0.42)/2.37 (0.42)
GE Double, EC, 1LE, air (6EC-6.3-LE6)	0.64/0.12	0.74/0.14	0.65/0.06	2.37 (0.42)/2.37 (0.42)
GXE Double, EC, 1LE, air (6EC-6.3-LE6)	0.64/0.03	0.74/0.03	0.65/0.00	2.37 (0.42)/2.37 (0.42)

(2) Angular Selective Glazings

Summary
These studies (Refs. 3, 4) investigated the energy performance of single and double pane angular selective glazings in a commercial office building module using a modified version of the DOE-2.1E energy simulation program. The module was located in the cooling-dominated location of Blythe, California. The angular selective glazings had varying solar and visible transmittance properties that were functions of the solar radiation incident angle. Our results show that the cooling energy performance of the single pane angular selective glazing is significantly improved by forming a double pane unit consisting of an outer pane angular selective glazing and an inner pane spectrally selective glazing. The daylighting energy performance of the single pane angular selective glazing is not affected very much by addition of the spectrally selective inner pane. We recommend that additional energy (DOE-2) and visual comfort (RADIANCE) studies be performed to better understand the angular selectivity variations at different times of the year. Also, energy use analysis should be done on a larger space to see what performance differences exist between angular selective and conventional glazings since the energy performance of the double pane angular selective window is very similar to more conventional windows.

Discussion
The energy performance of an angular selective window was analyzed by completing hour-by-hour
DOE-2 building energy simulations of a prototypical commercial office building module. The building module consisted of a 30.5m (100ft) square core zone, surrounded by four identical perimeter zones, each 30.5m by 4.6m (100ft x 15ft) facing four cardinal directions. Each perimeter zone was divided into ten office spaces of equal size with a floor-to-floor height of 3.7m (12ft) and floor-to-ceiling height of 2.6m (8.5ft). Each zone was assumed to have its own constant-volume variable-temperature HVAC system. The window-to-wall area ratio (window area expressed as a fraction of the floor-to-floor facade) was 0.30. Lighting power density was 16.1 W/m^2 (1.5 W/ft^2).

We analyzed the cooling and lighting energy performance of single pane and double pane angular selective windows. The angular selective glazing is being developed by the University of Technology in Sydney, Australia . Results were compared to several conventional insulated glazings in Blythe, California.

The direct solar transmittance (TSOL) and visible transmittance (TVIS) properties of the single pane angular selective glazing are seen on Figure 5 as a function of window surface solar altitude and azimuth. Values at normal incidence are 0.56 and 0.48 respectively. The solar heat gain coefficient at normal incidence is 0.64. U-factor was assumed to that for single pane clear glass. A spectrally selective glazing was was combined with the single pane angular selective glazing to form the double pane angular selective glazing with the solar/optical properties shown on Figure 6. TSOL and TVIS values at normal incidence are 0.31 and 0.38 with a solar heat gain coefficient of 0.39. Table 3 shows the solar/optical/thermal properties of the angular selective glazings and of the three conventional IG units that were used for comparison.

Figure 7 shows the annual cooling and lighting electricity use components in Blythe, California for north- and south-facing window orientations. For north-facing windows, there is not much variation in cooling energy performance with values ranging from 6.1 MWh (44 kWh/m2 floor area) for the low-E tinted glazing to 8.0 MWh (57 kWh/m2) for the single pane angular selective glazing. The double pane angular selective glazing requires 6.5 MWh (46 kWh/m2). For south-facing windows, cooling performance is mostly proportional to the window solar heat gain coefficient; however, the low U-factor of the double pane angular selective glazing does have a minimal positive affect on its performance. The single pane angular selective glazing requires the largest amount of cooling at 17.3 MWh (124 kWh/m2) and the reflective glazing the least at 8.7 MWh (62 kWh/m2). The double pane angular selective glazing requires 10.2 MWh (74 kWh/m2); the tinted grey requires 14.0 MWh (100 kWh/m2) and the low-E tinted requires 11.0 MWh (79 kWh/m2).

Lighting performance is a function of the visible transmittance of the glazings. The single pane angular selective glazing requires the least amount of lighting energy at 3.4 MWh (24 kWh/m2) for north-facing windows and 2.7 MWh (19 kWh/m2) for south-facing windows. The reflective glazing requires the largest amount of lighting energy at 5.7 MWh (41 kWh/m2) for windows facing north and 4.6 MWh (33 kWh/m2) for windows facing south. The double pane angular selective glazing varies from 4.1 MWh (29 kWh/m2) for the north and 3.3 MWh (24 kWh/m2) for the south.

The sum of the cooling and lighting electricity is also shown on Figure 5. For north-facing windows, the cooling and lighting energy are of the same order of magnitude; whereas, for a south orientation, the cooling energy can be substantially greater than the required lighting energy. The single pane angular selective glazing requires 11.4 MWh (82 kWh/m2) and the double pane angular selective glazing 10.6 MWh (76 kWh/m2) for windows facing north. The low-E tinted requires the least energy at 9.9 MWh (71 kWh/m2) and the reflective glazing the most energy at 12.0 MWh (86 kWh/m2). For south orientations, the single pane angular selective glazing has the largest rquirement at 20 MWh (144 kWh/m2). The double pane angular selective glazing requires 13.5 MWh (97 kWh/m2). The reflective glazing requires the least total energy at 13.3 MWh (95 kWh/m2 floor area); the tinted grey requires 17.0 MWh (122 kWh/m2) and the low-E tinted requires 13.8 MWh (99 kWh/m2).

These results indicate that additional studies are necessary to better understand the angular selectivity characteristics of these new glazings. Although the double pane angular selective glazing substantially reduced the amount of cooling energy required by a single pane angular selective glazing, its overall performance is not much different than conventional glazings. An hourly energy and visual comfort analysis using the DOE-2 and RADIANCE programs is warranted. Also, possibly a better use of angular selective glazings might be in a space that is larger than the one simulated. The space used in our study results in a lighting energy reduction due to daylighting that is very similar for both angular selective glazings and conventional glazings with the exception of the reflective glazing.

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TABLE 3
Commercial Building Energy Study
Angular Selective Solar/Optical/Thermal Properties

	SHGC(Tset)	SC	Tvis	U-Factor - COG W/m^2-K (Btu/h-ft^{2}F)
Angular Selective				
Single (6AS)	0.64	0.74	0.48	5.78 (1.00)
Double, AS, SS, air (6AS-12.6-SS6)	0.39	0.45	0.38	1.75 (0.30)
Conventional				
Double, Tint, air (6T-12.7-6)	0.47	0.54	0.38	2.74 (0.48)
Double, Refl, air (6RE-12.7-6)	0.17	0.20	0.13	2.35 (0.41)
Double, Tint, 1LE, air (6LE-12.7-6)	0.31	0.35	0.41	2.41 (0.42)

b. Residential Buildings

(1) Electrochromics:

Summary: Cooling Energy Performance

This study investigated the energy performance of electrochromic windows in a prototypical residential building under a variety of state switching control strategies. We used the DOE-2.1E energy simulation program to analyze the annual cooling energy and peak demand as a function of glazing type, size, and electrochromic control strategy. A single-story ranch-style home located in the cooling-dominated locations of Miami, FL and Phoenix, AZ was simulated. Electrochromic control strategies analyzed were based on incident total solar radiation, space cooling load, and outside air temperature. Our results show that an electrochromic material with a high reflectance in the colored state provides the best performance for all control strategies. On the other hand, electrochromic switching using space cooling load provides the best performance for all the electrochromic materials. Electrochromics compare favorably to conventional low-E clear glazings that have high solar heat gain coefficients that are used with overhangs. However, low-E tinted glazings with low solar heat gain coefficients can outperform certain electrochromics. Overhangs should be considered as a design option for electrochromics whose state properties do not change significantly between bleached and colored states.

Discussion

A single-story, slab-on-grade, one-zone house of wood-frame construction with a floor area of 143 m^2 (1540 ft^2) was modeled in two cooling dominated geographic locations: Miami, Florida (hot and humid) and Phoenix, Arizona (hot and dry). The cooling thermostat was set at 25.6C (78F) for all hours; heating setpoints were set at 21.1C (70F) from 7am to 11pm with a night setback to15.6C (60F) from 12pm to 6am.

The residence was modeled with windows facing north, east, south, and west. We varied the glazed portion of the window simultaneously on each facade at values corresponding to 0%, 2%, 4%, 8% and 12% of the residence floor area. Overall glazed area for the complete residence was therefore 0%, 8%, 16%, 32%, and 48% of the floor area. An external flush glazed thermally-broken aluminum frame was used for each window with a frame conductance of 4.6 W/m^2K (0.8 $Btu/hr\text{-}ft^2F$) and an area equal to 12% of the respective glazed area.

We compared the performance of six electrochromic windows as shown on Table 4. Two of the electrochromic materials have low reflectance levels typical of most devices; these are designated as types (80/20) and (80/10) representing the minimum and maximum visible transmittance levels of the electrochromic layer. These devices function primarily by changing absorptance and are intended to represent readily achievable performance. Two additional materials have reflectance levels that increase significantly in the colored state; these are designated (G) and (GX) and represent devices that may be available sometime in the future. Each of the two low reflective glazings, (80/20) and (80/10), was combined with either of two idealized types of low-E glazings. The first, which is designated (E) is a clear glass with a low emittance; the second, designated (S), is a spectrally selective glazing with the same emittance as the (E) glazing, but a greatly enhanced reflectance in the solar infrared.

The solar/optical properties of these electrochromic windows were varied using control strategies based on incident total solar radiation, space cooling load, or air outside air temperature. The performance of the electrochromic glazings were compared to three conventional double pane low-E glazings (Table 4). Three shading schemes were also modeled for use with the conventional glazings. These included an interior diffusing shade, an exterior obstruction, and an overhang.

Figure 8 presents annual cooling energy use for Miami for each of the electrochromic windows and controls strategies analyzed. Data are presented as a function of window area expressed as percent floor area with windows being equally distributed on each facade of the residence. The overall annual cooling energy use did not vary much between the two geographic locations. For a particular electrochromic material, performance for all control strategies is best with the spectrally selected glazing (S) than with the clear glazing (E). Also, for the six electrochromic window types, cooling energy is generally proportional to the lower value of solar heat gain coefficient of the electrochromic corresponding to the colored or switched state. Required cooling is about 4500 kWh (16.2 MJ) for a residence without windows in both Miami and Phoenix. As the window size increases, required cooling increases to a maximum value of 13700 kWh (49.3 MJ) in Miami and 12000 kWh (43.2 MJ) in Phoenix which occurs for the largest window area using outside air temperature control in Miami and incident solar radiation control in Phoenix. The smallest required cooling is obtained using space cooling load control; i.e., for the largest size window, the value is about 5100 kWh (18.4 MJ) in Miami and 6500 kWh (23.4 MJ) in Phoenix.

When using incident solar radiation to control state switching, as the setpoint range decreases, required cooling also decreases; but the differences in performance between each of the electrochromics increases. Decreasing the setpoint range yields cooling energy quantities that are more sensitive to the solar heat gain performance characteristics of the electrochromic, especially the solar properties near the colored state. As mentioned previously, space cooling load control of the electrochromics results in the lowest cooling energy requirements, and also the largest variation in performance for the different electrochromic devices, about 3650 kWh (13.1 MJ) for both locations. Space load control is an on/off device and all the electrochromics, regardless of orientation, are either bleached or colored with no intermediate state. This results in there being almost no difference in performance of the (E) and (S) type glazings because their colored states are very similar

Using outside air temperature for controlling electrochromic switching yields the largest performance difference between Miami and Phoenix. There is a significantly greater number of cooling degree days in Phoenix than in Miami, which results in lower electrochromic solar transmission properties and thus lower cooling energy requirements. In general, it does not seem advisable to use outside air temperature to control electrochromic switching.

We present data on Figure 9 for Phoenix to give some indication of electrochromic performance when compared to conventional glazings that use various types of shading devices to reduce cooling energy use. Results are shown for three low-E glazings that have very different solar gain characteristics and five shading systems. Also presented on each of these plots are data for the

GXE electrochromic glazing using incident solar radiation control with an intermediate setpoint range of 63-315 W/m^2 (20-100 $Btu/hr\text{-}ft^2$). The most cooling required for the largest size window occurs with the low-E clear glazing with the largest solar heat gain coefficient, SHGC=0.64: 15623 kWh (56.3 MJ) in Miami and 16879 kWh (60.8 MJ) in Phoenix. The least amount of cooling occurs with the low-E tinted glazing, SHGC=0.29, using combined exterior obstructions and overhangs or combined shades, obstructions, and overhangs: 6851 kWh (24.7 MJ) in Miami and 7520 kWh (27.1 MJ) in Phoenix. By comparison, the GXE glazing for the largest size window requires 7979 kWh (28.7 MJ) in Miami and 8287 kWh (29.8 MJ) in Phoenix.

References

5. R. Sullivan, M. Rubin, S. Selkowitz. "Reducing Residential Cooling Requirements Through the Use of Electrochromic Windows." Thermal Performance of the Exterior Envelopes of Building VI Conference scheduled for December 4-8, 1995 in Clearwater Beach, FL. LBL-37211 (1995).

TABLE 4
Residential Building Energy Study
Electrochromic Solar/Optical/Thermal Properties

	SHGC(Tset)	SC	Tvis	U-Factor - COG[Total] W/m^2-K (Btu/h-ft^{2}F)
	Bleached/ Colored	Bleached/ Colored	Bleached/ Colored	Bleached/ Colored
Electrochromic				
80/20E Double, EC, 1LE, air (6EC-6.3-LE6)	0.64/0.23	0.74/0.27	0.65/0.16	2.37 (0.42)/2.37 (0.42) [2.54 (0.45)/2.62 (0.46)]
80/20S Double, EC, 1SS, air (6EC-6.3-SS6)	0.52/0.20	0.60/0.24	0.65/0.16	2.37 (0.42)/2.37 (0.42) [2.54 (0.45)/2.62 (0.46)]
80/10E Double, EC, 1LE, air (6EC-6.3-LE6)	0.64/0.16	0.74/0.20	0.65/0.08	2.37 (0.42)/2.37 (0.42) [2.54 (0.45)/2.62 (0.46)]
80/10S Double, EC, 1SS, air (6EC-6.3-SS6)	0.52/0.15	0.60/0.17	0.65/0.08	2.37 (0.42)/2.37 (0.42) [2.54 (0.45)/2.62 (0.46)]
GE Double, EC, 1LE, air (6EC-6.3-LE6)	0.64/0.12	0.74/0.14	0.65/0.06	2.37 (0.42)/2.37 (0.42) [2.54 (0.45)/2.62 (0.46)]
GXE Double, EC, 1LE, air (6EC-6.3-LE6)	0.64/0.03	0.74/0.03	0.65/0.00	2.37 (0.42)/2.37 (0.42) [2.54 (0.45)/2.62 (0.46)]
Conventional				
Double, 1LE, Air (3-12.7-LE3)	0.64	0.75	0.77	1.81 (0.32) [2.04 (0.36)]
Double, 1LE, Air (3LE-12.7-3)	0.44	0.51	0.70	1.68 (0.30) [1.93 (0.34)]
Double, Tint, 1LE, Air (6LE-12.7-6)	0.29	0.33	0.41	1.67 (0.29) [1.89 (0.33)]

(2) Evacuated Glazings

Summary

This paper presents the results of a study investigating the energy performance of evacuated glazings or glazings which maintain a vacuum between two panes of glass. Their performance is determined by comparing results to prototype highly insulated superwindows as well as a more conventional insulating glass unit with a low-E coating and argon gas fill. We used the DOE-2.1E energy analysis simulation program to analyze the annual and hourly heating energy use due to the windows of a prototypical single-story house located in Madison, Wisconsin. Cooling energy performance was also investigated. Our results show that for highly insulating windows, the solar heat gain coefficient is as important as the window's U-factor in determining heating performance for window orientations facing west-south-east. For other orientations in which there is not much direct solar radiation, the window's U-factor primarily governs performance. The vacuum glazings had lower heating requirements than the superwindows for most window orientations. The conventional low-E window outperformed the superwindows for southwest-south-southeast orientations. These performance differences are directly related to the solar heat gain coefficients of the various windows analyzed. The cooling performance of the windows was inversely related to the heating performance. The lower solar heat gain coefficients of the superwindows resulted in the best cooling performance. However, we were able to mitigate the cooling differences of the windows by using an interior shading device that reduced the amount of solar gain at appropriate times.

Discussion

A prototype vacuum glazing consisting of two 4mm (0.16 in) thick low-E coated glass panes (e=0.27) separated by a 0.2mm (0.007 in) thick evacuated gap was evaluated. The unit has a solder glass hermetic edge seal and a grid of small ceramic pillars to maintain the spacing of the evacuated gap. We used the DOE-2 hour-by-hour program to simulate the annual and hourly energy performance in a heating-dominated location, Madison, Wisconsin. Madison is characterized by cold winters and hot and humid summers.

A single-story, slab-on-grade, one-zone house of wood-frame construction with a floor area of 143 m^2 (1540 ft^2) was modeled. Heating thermostat setpoints were set at 21.1C (70F) from 7am to 11pm with a night setback to15.6C (60F) from 12pm to 6am. Cooling was set at 25.6C (78F) for all hours. A direct-expansion air-cooled airconditioning unit was used for cooling and a forced-air gas furnace for heating. Cooling system COP was 2.2 and furnace steady state efficiency was 0.74.

Window performance was measured by considering different configurations using a base window size of 0.91m x 1.22m (3ft x 4ft). We varied the numbers of windows from 1 to 10 on one facade and rotated the building through 360 degrees in 45 degree increments. For 10 windows, the ratio of window area-to-wall area was 38.2% and window-to-floor area was 7.8%. We modified this approach by placing 1 to 10 windows on all facades simultaneously. For this case the window-to-floor area ratio was 31%. Four high thermal performance windows (Table 5) were simulated. The models were constructed using a generic wood-framed casement sill profile.

Results were also presented for two conventional windows that are currently in use in heating-dominated locations.

Figure 10 shows the incremental heating energy for the six glazings for the residential configuration in which ten windows are on one facade and the building rotated 360 degrees. The heating energy use for the building without windows was 73.2 GJ (69.4 Mbtu). We see that vacuum glazing #1 has the lowest required heating for all orientations. For orientations west-south-east, vacuum glazing #2 is the next best performer. Although the U-factor for these glazings is higher than the superwindow prototypes, their solar heat gain coefficient is also higher resulting in more beneficial solar heat gain and lower required heating.

For orientations approaching north where the amount of solar gain is reduced, we see that the U-factor becomes more important in determining performance. However, for these high performance, low U-factor windows, there is not much difference in heating performance for windows directly facing the north. Vacuum glazing #1 is equivalent to the R12.5 superwindow, followed by vacuum glazing #2 and the R8 superwindow. The relatively large U-factor of the conventional window results in a substantial heating energy increment when compared to the high performance windows. In general, for orientations west-south-east, one can expect a negative seasonal heating energy increment for most windows designed for heating-dominated locations, i.e. U-factors less than 1.70 W/m^2-K (0.30 Btu/h-ft^2F); as window orientations approach northwest-north-northeast, we begin to see positive heating energy increments.

Although this study was mainly concerned with the heating energy performance of windows, we also examined cooling performance since even in heating-dominated locations such as Madison, WI, there can be substantial cooling required during the summer months. Figure 11 presents the annual incremental cooling energy due to the window systems as a function of orientation. Data are shown for the building with ten windows on one facade. The average cooling energy use for the building without windows was 2.0 GJ (562 kWh, 1.9 Mbtu). Required cooling is primarily influenced by window solar heat gain and the results indicate a relatively proportional relationship between the two quantities. Although U-factor does have some minimal contribution to cooling, its effect is second order and can be ignored for high performance glazings.

We see from these results that the R12.5 and R8 superwindows outperform the vacuum glazings which in turn outperform the conventional low-E window and double pane clear unit. The R12.5 superwindow has the lowest solar heat gain coefficient (SHGC=0.40), while the double pane clear window has the largest, SHGC=0.76. The low-E conventional window has a SHGC of 0.74. Using a spectrally-selective low-E coating with a lower SHGC would improve the cooling performance of the conventional window; however, the heating performance would be adversely effected.

To mitigate these cooling differences, we also simulated a interior shading device that was implemented during the months April to September if the amount of transmitted direct solar radiation was equal to or greater than 95 W/m^2 (30 Btu/hr-ft^2). Under such a condition the solar heat gain through the window was reduced by 35% and there was a significant reduction in required cooling for the conventional low-E and vacuum glazing #1 windows for orientations south-southwest-west. Their performance approaches that of the R12.5 superwindow and is better than the R8 superwindow. The performance of vacuum glazing #2 for southwest-west orientations is almost the same as the R12.5 superwindow.

References

6. R. Sullivan, F. Beck, D. Arasteh, S. Selkowitz. "Energy Performance of Evacuated Glazing in Residential Buildings." ASHRAE Transactions V104 P2 (1996). LBL-37130 (1995).

TABLE 5
Residential Building Energy Study
Evacuated Glazing Solar/Optical/Thermal Properties

	SHGC(Tset)	SC	Tvis	U-Factor - COG[Total] W/m^2-K (Btu/h-ft^{2}F)
Highly Insulated				
Vacuum # 1				
Double, 2LE, vacuum (4LE-.15V-LE4)	0.68	0.78	0.71	1.00 (0.18) [1.29 (0.23)]
Vacuum # 2				
Triple, 3LE, vacuum, air (4LE-.15V-LE4-12.7-LE3)	0.58	0.67	0.60	0.73 (0.13) [0.95 (0.17)]
Superwindow # 1				
Triple, 4LE,xenon (3.2LE-6.4X-LELE-6.4X-LE3.2)	0.51	0.59	0.66	0.73 (0.13) [0.95 (0.17)]
Superwindow # 2				
Quad, 5LE, xenon (3.2LE-6.4X-LE-6.4X-LELE-6.4KX-LE3.2)	0.40	0.46	0.59	0.45 (0.08) [0.40 (0.13)]
Conventional				
Double, 1LE , argon (3-12.7A-LE3)	0.74	0.86	0.74	1.70 (0.30) [1.72 (0.30)]
Double, air (3-12.7-3)	0.76	0.87	0.81	2.79 (0.49) [2.67 (0.47)]